9. Consideration of Human Intrusion

9.1 INTRODUCTION

The containment requirements (§191.13) of 40 CFR part 191 specify that waste disposal systems must be capable of constraining movement of waste to the accessible environment for 10,000 years. To demonstrate this capability, DOE must show that there is a "reasonable expectation" of not exceeding specified release limits "from all significant events and processes that may affect the disposal system." Significant events and processes include those that are both natural and human-initiated. The final rule, 40 CFR part 194, includes specific requirements on human intrusion. These criteria are based on the assumption that inadvertent and intermittent drilling for resources is the most severe scenario to be considered when addressing human intrusion for performance assessment calculations because it provides a direct intersection with the waste and a pathway to the surface. Mining of resources is a very important, though less direct form of a human-initiated process or event. Under the provisions of the WIPP LWA, no surface or sub-surface mining or oil or gas production, including slant drilling from outside the boundaries of the sixteen square mile withdrawn area, is permitted with one exception. Directional (slant) drilling is permitted from outside the land withdrawal boundary into oil and gas leases in the extreme southwestern corner of the WIPP site, but only at depths below 6,000 feet. This depth is well below the repository horizon at 2,150 feet. EPA can make a determination after consulting with DOE and the Secretary of the Interior that DOE should acquire these leases to assure compliance with the disposal regulations.

The 40 CFR part 194 rule defines two types of human intrusion which must be considered in addition to mining:

- deep drilling events that reach or penetrate the level of waste in the disposal system
- shallow drilling events that do not reach the level of waste in the disposal system.

A variety of drilling events can be envisioned as occurring in the vicinity of the WIPP site. These include exploration and development drilling for oil and gas, exploration drilling for potash, drilling of water wells, and exploration drilling for other minerals. For example, water well drilling around WIPP is currently limited to geologic strata which lie substantially above the WIPP repository horizon—this would be defined as shallow drilling. Even though the wells are located in strata above the repository, if those strata became contaminated with radioactivity from the repository, water extraction could accelerate movement of radionuclides laterally to the boundary of the accessible environment or could directly transport contaminated water to the land surface which is also defined as part of the accessible environment.

This chapter provides background information related to possible human intrusion by drilling and by underground mining. The regional geology relevant to understanding human intrusion issues is described in more detail in the following section. Subsequent sections discuss specific drilling and mining issues.

9.2 GEOLOGIC SETTING

Understanding the regional geology is an essential step in developing a defensible description of human intrusion which might impact the WIPP repository. The WIPP is located in the northern part of the Delaware Basin, which is a large sedimentary basin in Southeastern New Mexico and West Texas. This deep oval-shaped structural depression, which is about 135 miles long and 75 miles wide (COO71), was an embayment covered by a deep sea (i.e., 305 to 245 million years before present [Ma]). Sedimentation within the basin resulted in formation of thick marine strata. Organic activity at the margins of the basin produced carbonate reefs -- the present day Capitan Reef -- that separated the deep-water sediments from the shallow-water shelf deposits which developed landward from the reefs (SAN92). The depositional process, as described by Cooper and Glanzman (COO71), is summarized as follows:

> The irregular floor of the sea was characterized by structural basins, platforms and broad shelves. Fine sand and limestone accumulated in the basins; reefs formed on the margins of the shelves and platforms; limestone and sand accumulated immediately behind the landward side of the reefs; and gypsum, anhydrite, and other evaporite rocks, and silt and clay accumulated in the shallow waters of the shelves. Eventually, the reef growth was halted by increasing the salinity of the sea water and evaporite sediments (Castile, Salado, and Rustler Formations) were deposited in the Delaware Basin. Evaporite deposition was interrupted during two intervals of time, during which the water was less saline and limestone was deposited. Toward the end of

> Permian time, deposition of the evaporite rocks ceased and deposition of terrestrial red beds (Dewey Lake Redbeds) began. Terrestrial deposition continued during parts of Triassic time. Additional thin deposits of sediments accumulated in Quaternary time. A total of 18,500 feet of sedimentary rocks were deposited in places in the Delaware Basin.

The region surrounding the WIPP may be characterized in terms of the geologic composition of the sub-surface features, the hydrologic properties and the history of hydrocarbon (i.e. oil and natural gas) accumulation. The horse-shoe shaped Capitan Reef was formed by the deposition of organic material which differs from the non-organic material which developed into the evaporite salt formations which lie along the interior. King noted this distinction when concluding that the Capitan Reef was separate from the Delaware Basin.

> The rocks of the Guadalupe Mountain region were deposited near the edge of a feature of Permian time known as the Delaware Basin, along whose margin they show complex changes in facies. The rocks laid down outside the basin, in what is here termed the shelf area, are thus very different from contemporaneous basin deposits. (KIN42)

The "complex changes in facies" referred to by King result from the geologic dissimilarities of the carbonate Capitan Reef from its contemporary, the evaporite Bell Canyon formation which adjoins the Capitan Reef on the interior side. (The WIPP is located within the Salado Formation, which is a sequence of evaporite rocks deposited in the Late Permian Epoch (258-245 Ma). A portion of the stratigraphic column that represents this depositional sequence is shown in Figure 9-1 (WEI77).) The Guadalupe Mountains or shelf area, noted by King, in fact contain a portion of the Capitan Reef. Other authors, including Cooper and Glanzman, quoted earlier, have remarked as well upon this distinction: "This structural [Delaware] basin is generally considered to be the area surrounded by the Capitan Limestone [i.e. the Capitan Reef]."

Subsequent to its formation, the hydrologic properties of the Capitan Reef were enhanced by fracturing and dissolution such that the effective porosity of the Capitan Reef increased. Partially as a result of this, the Capitan Reef is today a significant aquifer in the region and is a major source of water for the City of Carlsbad. In contrast, the salt formation which

Figure 9-1. Stratigraphic Column and Potential Hydrocarbon Pay Zones (Source: POW78) contains the WIPP, known as the Salado, has a small primary porosity combined with a lack of transmissive fractures, and thus groundwater flow through the Salado is not significant. The interior regions as a whole are noteworthy for the relative scarcity of potable groundwater.

Over the geologic history of the Delaware Basin, oil and natural gas have accumulated underneath the Capitan Reef. Although formed in the interior portions from organic material, the hydrocarbons preferentially migrated outward until being trapped by the cap-like profile of the underside of the Capitan Reef. Organic material which generates hydrocarbons did, in fact, exist in the interior portions and was deposited during the middle and late Permian era, but as Hills describes (HIL84), the ultimate fate of the hydrocarbons lay elsewhere: “The hydrocarbons contained in the source beds [in the regions within the Capitan Reef] migrated primarily to interbedded sandstone reservoirs within the [Delaware] basin and later to the porous carbonate reservoirs on the margins.” This “trapping mechanism” possessed by the Capitan Reef does not have a parallel in the interior portions, such as the Salado and Bell Canyon formations. Hills described this difference: “no large Upper Permian structural traps were formed in the [Delaware] basin, and most hydrocarbons migrated to the surrounding shelves [i.e. the Capitan Reef].”

Various estimates of the area of the Delaware Basin have been cited by different authors. In most cases, neither the basis for the estimate nor whether the cited area includes or excludes the Capitan Reef is mentioned. For example, Hills (HIL84) said the area is about 13,000 square miles (33,500 km^2) while Richey et al. mention that the area (which presumably includes the Capitan Reef) is about 12,000 square miles (31,000 km^2). This same area is cited without attribution by Powers et al. (POW78, v. 1, pp. 3-59). An earlier site selection report had noted that "the area of the Delaware Basin was assumed to be about 30,000 km^2 (CLA74). These differences are not surprising since the boundaries of the Basin mostly lie below the surface and the estimates were intended for descriptive purposes rather than quantitative analysis.

To obtain better quantitative values for the Basin area, the area on several maps was measured using standard software designed for operation with geographic information systems. The areas of the Delaware Basin as depicted in Figure 1 in HIL84, in Figure 3.4-1 of POW78, and Figure 6.3-8 of POW78 were calculated with results as follows:

- HIL84, Figure 1 — 28,000 km^2
- POW78, Figure 3.4-1 — 30,200 km^2
- POW78, Figure 6.3-8 — 25,200 km^2

POW78, Figure 6.3-8 indicates more detailed mapping of the basin boundary and the surrounding Capitan Reef. Various versions of this figure are widely used in the technical publications prepared by Sandia National Laboratories for the WIPP project. This representation of the Delaware Basin embracing 25,200 km^2 is reproduced in Figure 2-2 and is appropriate for estimating intrusion rates.

9.3 INTRUSION BY DRILLING

9.3.1 Oil and Gas Drilling

Drilling for oil and gas has been conducted in the Delaware Basin since the turn of the century. Over the past decade, drilling for oil and gas in the vicinity of the WIPP site has increased significantly (SIL94). Typical oil drilling targets within the Delaware Basin around the WIPP site include Permian age rocks such as the Cherry Canyon and Brushy Canyon Members of the Delaware Mountain Group and the Bone Springs Formation. The tops of these geologic formations lie about 5,700 feet and 8,300 feet below the land surface (GUZ91a). These formations were not generally recognized as exploration and development targets until the late 1980s because their reservoir production characteristics were not well understood (NBM95). However, recent improvements in borehole logging procedures have allowed petroleum geologists to determine which Delaware Mountain Group sediments have a high potential for fluid hydrocarbons.

Gas drilling targets reside in the Pennsylvanian age Strawn, Atoka, and Morrow formations at depths of about 12,700 feet, 13,200 feet, and 13,700 feet below the surface, respectively. All current oil and gas targets are below the WIPP repository horizon and would be defined as deep drilling under 40 CFR part 194.

Data on oil and gas drilling are available from a variety of sources. In New Mexico, the U.S. Bureau of Land Management and State of New Mexico Oil Conservation Division keep records on wells that have been issued permits. In Texas, this information resides with the Texas Railroad Commission. Borehole information is also obtainable from commercial data

Figure 9-2. Outline of the Delaware Basin (Source: POW78, Figure 6.3-8) bases such as that managed by the Petroleum Information (PI) Corporation in Denver, Colorado. The earliest Delaware Basin information in the PI data base indicates that five holes were drilled between 1909 and 1914. Four of these holes were in Texas and one was in New Mexico.

9.3.1.1 Permitting Practices

In order to conduct oil and gas drilling, a permit must be obtained either from the U.S. Department of the Interior, Bureau of Land Management (BLM)—if Federal lands are involved—or the Oil Conservation Division (OCD) of the State of New Mexico Energy, Minerals, and Natural Resources Department—if state or private lands are involved. Drilling activity on Federal lands is regulated under 40 CFR part 3160 (Onshore Oil and Gas Operations; Federal and Indian Oil and Gas Lease: Drilling Operations: Final Rule, November 18, 1988). The regulation prescribes minimum levels of performance and enforcement action when rules are violated. Procedural requirements are not included. OCD Rules and Regulations are more specific than those of 40 CFR part 3160 and BLM often follows specific OCD practices. Many detailed procedures—including well casing practices, well completion, and methods of borehole sealing—requiring BLM or OCD approval are area specific, not included in regulations, and not always in writing.

OCD Rule 104 specifies the maximum density for oil and gas wells. Wildcat (i.e., exploration) gas wells in Eddy and Lea Counties of New Mexico are granted a minimum spacing of 160 acres for drilling depths of less than 11,000 feet, or 320 acres if drilled to greater than 11,000 feet. Development (i.e., production) gas wells are also limited to one per 160 or 320 acre tract.

The minimum spacing for wildcat and development oil wells in these two counties is 40 acres. There is also a limit of four development wells per tract when special pool rules apply. However, more wells are allowed if the tract is permitted for active secondary recovery. In each case, oil and gas wells must also conform to boundary offset distances, placing each well within a specified area within a tract. In the absence of secondary recovery operations or special pool rules, the spacing requirements thus allow up to 6.2 oil wells/km^2 or up to 1.5 gas wells/km^2 for each potentially productive formation. BLM follows OCD well spacing rules although they are not legally required to do so. BLM also requires an environmental assessment before a permit is granted.

9.3.1.2 Well Drilling and Casing

After the permit is granted, the drilling contractor will set up equipment at the drill site. For deep holes drilled around WIPP, about 7-10 days are typically required to prepare the site, set up the drill rig, construct the mud pits, and set the surface conductor casing to secure surface sediments before drilling commences.

The drilling of a gas or oil well usually requires a program involving two or more bit sizes to complete a borehole and one to four bit changes per borehole (BER94) to change worn or damaged drill bits. A typical gas or oil well starts with a large diameter hole at the surface into which a conductor pipe is placed. A smaller size drill bit which can pass through the conductor is used to drill a hole to accommodate the surface casing, through which a still smaller bit passes to drill for the production casing. Should bottom hole conditions warrant, a liner may be inserted in the lower portion of the production casing. The bottom hole is usually a minimum of 2 to 3 inches in diameter and telescopes outward to the larger diameters required to accommodate uphole conditions.

The OCD has specified for the past decade or more that all gas and oil wells on New Mexico state and private lands (with minor exceptions) be drilled in the $17^{1/2}$, $12^{1/4}$, and $7^{7/8}$-inch diameter size sequence. As each step in the drilling sequence is completed, the drill string is removed from the borehole and the hole is lined with tubular steel casing which is set in place with cement. The larger diameter surface casing is set from the surface to the top of the Rustler Formation at a depth of about 500-600 feet. The next drilling sequence is initiated which involves penetration of the salt section (the Salado and Castile formations). When the hole reaches the bottom of the Castile at a depth of about 4,000 feet, the drill string is again removed from the borehole and the intermediate casing is set. After the intermediate casing is set, drilling is reinitiated and continues until the target horizon, for example, the Cherry Canyon Formation of Delaware Mountain Group, is reached and the production casing is then set. This size sequence appears also to be the current common practice for drilling on Federal lands administered by the BLM.

OCD records indicate that a two casing program was used during the 1970s and earlier, in which smaller bits and casings were common. A frequent practice in a two-casing run was to combine the surface and intermediate casing intervals into one extending from the surface to a depth of 2,000 to 4,000 feet above the production zone before a smaller bit was used. A drilling sequence of $10^{3/4}$ or $12^{1/4}$-inch bit followed by a $7^{7/8}$-inch bit was most common for this practice, though no count has been made as to the number of such wells. Gas wells have been completed at depths ranging from 10,000 to 16,000 feet deep and oil wells have been completed at 5,200 to 8,200 feet deep. Drilling and completion of the well typically take about 100 days. Virtually all gas and oil wells in the area are drilled to depths which would penetrate the WIPP horizon.

OCD Rule 107 imposes a number of requirements concerning casing, tubing, cementing, etc., for wells being drilled and completed. Section III8 of 43 CFR part 3160 establishes similar requirements for Federal lands. However, in all cases the detailed procedures for specific locations are not in the regulations and are specified by the appropriate District Offices. OCD states that they inspect 100% of new wells being drilled, cased, and completed. BLM inspects wells under its jurisdiction on a random, less than 100%, basis.

If the WIPP site were to be penetrated by inadvertent human intrusion, such an event would occur during drilling through the salt section before the intermediate casing is set. Once the intermediate casing is set in place and the annulus between the casing and the borehole wall is sealed with cement, then the possibility of radionuclide contamination reaching the surface will be prevented as long as the casing remains intact. Typically, casing integrity is demonstrated by pressure testing and ultrasonic logging of the cemented section for bonding between the casing and the cement and between the cement and the formation. It is estimated that this critical section of a borehole would remain uncased for no more than three days during drilling. While there is no solid data base which describes the frequency of occurrence of improperly cased holes or holes with casing failures, such failures have been reported (KIR94).

9.3.1.3 Detection of the Repository During Drilling

A key question when developing the possible range of human intrusion rates to which the WIPP repository might be subjected, is whether the drilling contractor is likely to detect the presence of the WIPP repository during drilling for oil or gas. The drilling operator could penetrate the WIPP and not realize he had done so. Assuming his drill hole was successful and the anticipated oil pool or gas reservoir was reached, he might drill additional development wells to exploit the resource. These additional holes might also penetrate the waste and be undetected.

Because of the nature of drilling practices employed in the Delaware Basin, the existence of the WIPP may not be revealed by a borehole which intersects the repository. Drilling is typically done by independent drilling contractors whose main goal is to "make hole" and efficiently meet the contract requirements. Drilling through the salt section is typically at a rate of 50 to 100 feet per hour, so only about 8 to 15 minutes would be required to penetrate the repository (based on room height prior to creep collapse of the repository). J. W. Berglund of the New Mexico Engineering Research Institute states, "While in the salt section, drilling mud (brine) is supplied from a large, plastic lined reserve pit dug in the ground with a surface area of about 4,000 ft^2. Drilling mud is pumped from the reserve pit down through the drill pipe and drill bit and up the annulus formed by the drill string and drilled hole. The drilling mud and the drill cuttings are returned directly to the reserve pit where the cuttings settle out. While drilling in the salt section, no formal attempt is made to monitor the character of the cuttings or the fluid volume of the reserve pit. A gas analyzer is not attached to the returns until the hole is much deeper than the depth of the WIPP repository" (BER95).

Even if gas flows were generated when the drill bit intersected the WIPP, this event would more likely be interpreted as a release from naturally occurring gas pockets. If the drill bit encountered brine from the WIPP, this too might be interpreted as a naturally occurring phenomenon. Naturally occurring gas and brine pockets are commonly found in the sedimentary rocks above and below the WIPP horizon in the Delaware Basin. Brine pockets are encountered during drilling of deep boreholes into the Castile Formation below the repository, and to a lesser extent into the Salado Formation above the WIPP horizon. For example, records available at the OCD office in Artesia, NM, reveal that a brine flow blowout (back pressure in the drill stream sufficient to cause actuation of over-pressure relief valves to protect piping from damage) occurred for a recently drilled well (API no. 30-015-27406) (S2, T18S, R30E) at a depth of 898 feet below the surface which is a few feet into the McNutt potash zone of the Salado Formation. Drilling was temporarily halted for four hours during which the flow rate was estimated at 40 to 50 barrels per minute (1,680 to 2,100 gpm). The hole was shut in and allowed to pressurize to 350 psi. Drilling of the $12^{1/4}$-inch diameter hole resumed to a depth of 1,555 feet. Casing was set and cemented. As the brine inflow was similar in characteristics to the brine water drilling fluid being used, no apparent effect was seen except for the break in drilling.

Gas kicks (blowouts) also occur in the Salado Formation in which the WIPP is located. When these are encountered, drillers routinely let the drilling mud blow from the hole—this appears as a cut brine solution when drilling through the salt section—with no effort to retard the blowouts by closing blow-out preventers on the drill rigs. These kicks are of short duration and when completed, drillers restart mud circulation and adjust the drilling mud to the desired weight. Presence of these small pockets of water or nitrogen has been detected both by mining and drilling (COO71). The largest cavity found through 1971 was about 176 m^3 and was not pressurized—at least when discovered by mining (CLA74). There are at least seven reported incidents of pressurized gas blowouts in potash mines. Two of these resulted in fatalities (CHA84).

Brine inflows from Castile Formation brine reservoirs are well documented for two wells—ERDA-6 (S35, T21S, R32E) and WIPP-12 (S17, T22S, R32E)—in which the initial inflow was 20 gallons per minute (gpm) and 350 gpm, respectively. The brine reservoirs were estimated at 26.5 million gallons total for ERDA-6, with 69,000 gallons flowing to the surface during testing, and 714 million gallons total for WIPP-12, with 3.3 million gallons to the surface (POP83). Although historic information is vague and incomplete, similar-sized brine reservoirs were observed in: 1) Mascho-1 (S20, T22S, R33E) drilled in 1937 which had a reported initial flow of 230 gpm, 2) Belco (S25, T23S, R30E) drilled in 1974 with an initial inflow of 350 gpm while flowing for 26 hours, and 3) Shell (S36, T22S, R32E) drilled in 1964 with an initial inflow of 580 gpm. Brief commentary on these wells (POP83) describes stopping of drilling operations until artesian flow is completed, followed by a resumption in drilling. Recent interviews with drillers substantiated this practice. Brine pocket blowouts are like gas kicks, in that they cause no problems beyond drilling breaks. In one well, Pogo (S26, T21S, R31E), a moderate weight drilling mud (15 pounds per gallon - ppg) was applied after four days of flow. Whether the flow was really stopped by this weight of mud or whether the reservoir pressure was exhausted is unknown. A similar weighted mud of 12 ppg did not stop the inflow at another well drilled in 1962.

9.3.1.4 Borehole Plugging and Abandonment

When a borehole is no longer useful it must be plugged and abandoned according to specified procedures. One mechanism identified for releasing wastes from the WIPP repository is the escape of waste-generated gas or contaminated brine through an unsealed or improperly sealed borehole. In some scenarios used to assess the performance of the WIPP, boreholes, plugs, or seals are assumed to remain intact for the full regulatory period, and in some cases the seals are assumed to degrade. Effectiveness of borehole seals is important to maintaining the integrity of the WIPP repository. Borehole permeability was identified in the 1992 WIPP PA as one of two critically important parameters (SAN92).

The New Mexico OCD Rules and Regulations (OCD93) pertaining to sealing off geologic strata and notification are covered in Rule 106, which requires protection of oil- and gas-producing strata from each other and from overlying water strata. Also, "All fresh waters and waters of present or probable value for domestic, commercial or stock purposes shall be confined to their respective strata and shall be adequately protected by methods approved by the Division." OCD Rule 202 (Plugging and Permanent Abandonment) requires prevention of the contamination of fresh waters. The Rules and Regulations define fresh water as less than 10,000 mg/l total dissolved solids (TDS). An underground source of drinking water is defined as an aquifer having less than 10,000 mg/l TDS and containing a sufficient quantity of water to supply a public water system, unless it has been exempted. The Federal regulations also require protection of usable water which means generally those waters containing up to 10,000 ppm of total dissolved solids.

OCD Rule 101 requires a surety bond, payable to the State of New Mexico, before new wells can be drilled. The purpose of this bond is to pay for the proper plugging, sealing, and abandonment of the well if the owner is financially unable to do so in the future. In Eddy and Lea County, the amount of this bond varies from $5,000 to $10,000 per well, depending on well depth. Alternatively, a blanket plugging bond of $50,000 can be obtained to cover all wells drilled by an operator. The BLM also has bonding requirements for new wells, although the adequacy of this program has been questioned by the Department’s Inspector General (DOI92). Large numbers of older wells on both Federal and non-Federal lands do not have adequate plugging bonds, and the State and Federal Government's financial obligation to seal and abandon these wells properly may be significant.

OCD Rule 201 requires a well be either properly plugged and abandoned or temporarily abandoned within 90 days after: (1) a 60-day period following suspension of drilling operations, (2) a determination that a well is no longer usable for beneficial purpose, or (3) a period of one year in which a well has been continuously inactive. Despite these requirements, the current status of a large number of wells under OCD regulations is unknown (OCD94). Audits by DOI Office of Inspector General reveal a significant unknown well status problem also exists on BLM lands (DOI89, DOI92).

OCD Rule 202 requires written notice on Form C-103 at least 24 hours in advance of commencing any plugging operations. Verbal approval of the method of plugging and time to begin is permissible for a newly drilled dry hole. The well operator is required to notify the OCD after plugging and site clean-up operations for an inspection of the well and location. However, the operator has up to one year after completion of plugging operations to complete the site clean-up. The Federal Abandonment Requirements, contained in 43 CFR part 3160 III G, specify details of cementing, plugging, and capping boreholes, but do not identify any procedural requirements. Field interviews suggest that 100% of all holes under OCD aegis are inspected, and less than 100% of holes drilled under BLM aegis are inspected for compliance with plugging regulations.

OCD Rule 203 describes conditions under which a well may be temporarily (rather than permanently) abandoned. Temporary abandonment can be for a period of up to 5 years and the operator can apply for renewal at the end of this period. In seeking renewal, the operator is required to test the integrity of the casing with a specified procedure and provide evidence that there will not be migration of water or hydrocarbons between strata.

BLM proposed procedures for reviewing the status of non-producing wells following findings in a 1989 Inspector General Audit Report (DOI89) that large numbers of wells had been inactive for years without meeting BLM's procedures or requirements for temporary abandonment. The 1992 follow up audit report did not consider implementation of these procedures to be adequate. After the 1989 audit, BLM had proposed procedures for reviewing the status of non-producing wells. These proposed procedures would require that BLM field offices review the status of non-producing wells listed monthly and determine whether each well was usable for further oil and gas production. The procedures would also require that the field offices request the operators to either submit a justification for shut-in status, obtain temporary abandonment approval, plug and abandon the well, or resume production. If implemented, the Inspector General felt that its 1989 recommendation would be satisfied (DOI92). However, the Inspector General advised the Secretary of the Interior on March 20, 1992 that BLM did not agree with the Inspector General's recommendation to devote resources and management oversight to improve the Inspection and Enforcement Program.

Gas and oil wells are usually plugged in two ways. Plugs are either placed inside the production casing or inside the intermediate casing when the upper portion of the production casing is removed. In either situation, plugging is performed within a cased hole. As noted previously, in gas and oil wells in the Delaware Basin, surface casing extends from the surface to the bottom of the Rustler Formation and is cemented in place, thereby rendering it permanently fixed. The intermediate casing which is placed inside the surface casing extends from the surface through the salt section and terminates at the bottom of the Castile Formation (a depth of approximately 3,600 feet at the WIPP). This intermediate casing is cemented from bottom to surface and is likewise permanently fixed in place. The production casing which extends from the surface to the Delaware Mountain Group strata for oil or deeper to the Morrow or Strawn Formations for gas may either be cemented inside the intermediate casing from bottom at 6,000 to 8,000 feet deep to the surface, or it may only be cemented for the lower 3,900 feet, thereby allowing the removal of several thousand feet of the inner casing string when the well is abandoned. At least one, and sometimes two, cement-shrouded casing strings separate the WIPP horizon rock from the open hole. A four-part casing is unlikely in the vicinity of the WIPP since four casing strings extending from the surface are required by the OCD only over the Capitan Reef. For deep gas wells incorporating a liner, the fourth inner string is hung from the lower portion of the production casing and does not extend into the intermediate casing.

All downhole tools and fluids are removed from a typical gas and oil well prior to abandonment. A class "C" type cement plug is placed at intervals throughout the hole starting at the guide shoe of the inner casing string (usually the production casing) which has not been drilled out but was previously cemented in place when the inner casing string was set. The inner casing is usually set to the bottom or below the producing zone and perforations are made in the casing for a length of up to 100 feet above the guide shoe. Plugs are placed at the top of each producing formation followed by intermediate plugs, plugs at the bottom and top of the salt section, and a surface plug. Each plug is about 35 feet thick and is placed at intervals no greater than 2,000 feet as specified by OCD. Drilling fluid is placed between each plug.

The position of each plug is carefully monitored because the plug can slip before it sets. Cement plugs are more dense than the fluid upon which they rest and can possibly move or disintegrate into the fluid before hardening. An OCD field representative certifies the placement of each plug for holes on state and private lands before the next interval of fluid is placed.

Field investigations failed to uncover any long-term monitoring of borehole seal integrity. Neither the BLM nor OCD conducts follow-up studies after borehole seals have been installed. The American Petroleum Institute, recognizing that "an unknown but large number of abandoned wells exist that are unplugged or inadequately plugged by today's standards," conducted an analysis of whether abandoned wells could act as conduits to move saline water from deep underground to more shallow-lying underground drinking water sources (WAR90). The studies focused on brine flow from the Lower Tuscaloosa Sand, a mature oil-producing trend in Mississippi and Louisiana at a depth of about 10,500 feet, to the Sparta sands and shales, the drinking water source which bottoms at about 3,100 feet. A nearby injection well in the Lower Tuscaloosa was assumed to provide the driving force for flow in the abandoned well. Two scenarios were examined, viz.:

- Uncased well scenario — The upper 1,500 feet of the well are cased and cemented, but the balance of the borehole remains open. In time, overlying shale sloughs into the hole to form a 154.5 foot column of shale with a porosity of 3% and a permeability of 0.0001 Darcy. Above this is a 4,620 foot column of settled solids from the drilling mud having a porosity of 84% and a permeability of 0.001 Darcy.

- Cased well scenario — The well is cased from top to bottom and the lower 2,000 foot production casing is cemented. The annulus between the balance of the casing and the borehole is left filled with drilling mud. It is assumed that a corroded interval develops in the casing at a depth of 6,000 feet.

The two scenarios modeled using the SWIFT III computer code indicated that—over the range of injection rates considered (20 to 600 barrels per day)—there was no flow into the underground drinking water source. Thus, for the conditions examined, unplugged or poorly plugged boreholes were not a problem. One should also note that the permeabilities used in the API study are about four orders of magnitude lower than used by SNL in the 1992 WIPP PA (SAN92, Volume 3).

Currently, all dry holes from gas and oil exploration are plugged per federal and state standards. Producing wells are not monitored, nor are abandoned formerly-producing wells certified as plugged. Whereas OCD conducts an active program of institutional control for all new wells on state and private lands, BLM performs only random and infrequent checks on new wells located on Federal land. The number of unplugged boreholes drilled prior to the more stringent institutional controls now employed is unknown, but has been characterized as "many" by OCD field personnel.

The 40 CFR part 194 rule assumes that natural processes will degrade or otherwise affect the permeability of boreholes over the regulatory time frame. The issue of unsealed or improperly sealed boreholes must also be factored into analysis of the repository integrity.

9.3.1.5 Human Intrusion Scenarios

In addition to the radioactivity release scenarios involving direct transfer of waste to the surface by a borehole which penetrates the repository, several other scenarios involving human intrusion can be theorized. For example, SNL developed a family of scenarios involving boreholes which penetrate the waste and are then plugged above the overlying transmissive Culebra Member of the Rustler Formation. Solubilized waste then moves up the borehole by brines found in underlying formations and then, due to the borehole seal, laterally through the relatively transmissive Culebra toward the WIPP site boundary (SAN92). The assumption of borehole sealing depth is consistent with the sealing practices in the area and the regulatory requirements. The assumption is also reasonably analogous to the other geologic systems that were analyzed so that DOE should be able to defend the above scenario.

Conceivably some boreholes would miss the waste, but be drilled sufficiently near the disposal region to encounter contaminated brine and rock in, for example, Marker Bed 139, a brittle, fractured anhydrite layer, which immediately underlies the repository.

9.3.2 Exploratory Drilling for Potash

Potash is the generic name for various potassium salts often formed by the evaporation of natural brines whose potassium content is normally expressed in terms of equivalent K_2O. Additional background information on potash mining is included in Sections 9.4.1.

The potash reserves and resources[1] at WIPP lie within the McNutt potash zone of the Salado Formation. The depth of the 11 identified ore zones in the McNutt, based on the ERDA-9 borehole, ranges from about 1,372 feet to 1,741 feet near the WIPP site (POW78) and the

[1] According to GUZ91b, reserves are those resources that are currently economically recoverable with currently available technology, and resources are mineral deposits that are not currently economical or have not been discovered.

McNutt dips generally to the east (CHE78). As noted above, the WIPP repository is located in the Salado at a depth of 2,150 feet. The deepest potash resources are thus about 400 feet above the waste repository. These ore zones vary widely in thickness and mineralization. The zones are not continuous across the Delaware Basin, and certain ore zones are not present in some of the boreholes evaluated. Even when mineralization is present in an ore zone, it may not be sufficient to be of commercial interest. In some cases, mineralization is absent altogether.

The potash resources of the Designated Potash Area (so designated by the Secretary of the Interior, see 9.4.1) lie roughly in an alignment extending from northwest to southeast. Early potash mining started along the northern and western fringe of the district and moved in southerly and easterly directions into the Delaware Basin. Exploratory boreholes have preceded the underground workings, thereby delineating the reserves for further exploitation. Potash boreholes tend to cluster around these mines with occasional boreholes located far-afield.

Exploration drilling is conducted in the area to delineate additional ore reserves. Since this drilling is generally to depths of less than 2,150 feet (except to the east where the ore zones dip downward), this event would be characterized as shallow drilling by 40 CFR part 194. Drilling for potash is significantly different from drilling for oil and gas. In addition to being more shallow, the holes are also smaller in diameter. Approximately 1,892 potash coreholes have been drilled in the Delaware Basin (per BLM estimate), mostly within the designated boundary of the Known Potash Leasing Area. Potash boreholes typically have been drilled either into an undesignated competent stratum of the upper Salado Formation or into the Vaca Triste Sandstone member, which forms the upper contact with the McNutt. The size distribution for all holes examined can be grouped into Rustler Formation drill bit sizes of $5^{1/2}$ inches to $8^{3/4}$ inches in diameter and Salado Formation core bit sizes of $3^{1/2}$ inches to $5^{3/16}$ inches in diameter. After a surface casing is set through the Rustler Formation—sometimes extending into the upper Salado Formation—core bits are used to drill through eleven ore zones in the McNutt potash zone. The cored section of the hole is not cased. The bit size distribution is as follows:

Bit Diameter Distribution

Rock Bit Dia.:	$8^{3/4''}$	$8''$	$7^{7/8''}$	$6^{11/16''}$	$6^{1/2''}$	$6^{1/4''}$	$5^{5/8''}$	$5^{1/2''}$
Percentage:	6%	2%	8%	2%	6%	57%	17%	2%

Core Bit Dia.:	$5^{3/16''}$	$4^{3/4''}$	$3^{15/16''}$	$3^{7/8''}$	$3^{1/2''}$
Percentage:	1%	3%	12%	54%	30%

Most of the potash holes are terminated at or near the lower contact of the McNutt. Three test holes drilled by the U.S. Geological Survey (USGS) were about 2,000 feet deep (JON78) near the WIPP site. Holes as deep as 2,800 feet have been logged in contiguous townships.

Based on discussions with BLM personnel, potash drilling has occurred over a period of about 70 years. (This is consistent with the fact that the U.S. Bureau of Mines (SEA94) has reported saleable potash production from New Mexico since 1933 and records ore grades as early as 1930.)

BLM has a permitting procedure similar to oil and gas for exploratory potash coreholes on Federal lands. The State Engineer requires approval for drilling of potash coreholes on non-Federal lands if the drilling is through artesian aquifers or other water zones that require protection. This requirement may not affect all locations around the WIPP site since the Rustler Formation is not considered artesian.

Under a scenario that includes drilling for potash, all potash boreholes would pass through the Culebra Member of the Rustler Formation. If a borehole contacted a contaminated plume of Culebra water resulting from a prior human intrusion into the repository, it would bring at least as much contaminated fluid to the surface as was in the volume of the Culebra rock intercepted by the borehole. Furthermore, any radionuclides adsorbed on the solid material would also be brought to the surface. For a 7.0 m thick Culebra aquifer with 0.16 porosity, a 6 inch (15 cm) borehole would bring a bulk volume of 0.128 m^3 to the surface. This volume would contain 0.021 m^3 of fluid. Assuming solubilities of 10^{-6} M for plutonium and americium and 10^{-4} M for uranium results in a concentration of about 0.9 Ci/m^3.

Considerably greater quantities of radionuclides could be present in the solid material brought to the surface if surface adsorption in the Culebra is considered. The concentration (C_s) of an element (e.g., Pu, Am, U) in the solids can be shown to be:

$$C_s(g/cm^3) = r_s(g/cm^3)*Kd(cm^3/g)*C_{brine}(g/cm^3)$$

where r_s is bulk density of the solids (about 2.0 g/cm^3) and Kd is the solute distribution coefficient.

In the 1992 PA (SAN92), SNL sampled on a matrix Kd value for plutonium from zero to 100,000 cm^3/g with a median value of 261 cm^3/g. Thus, for the median Kd value the concentration of plutonium in a cubic centimeter of rock is 522 times that in a cubic centimeter of fluid. Since there is only 0.16 as much fluid volume as rock volume in the Culebra (i.e., the porosity is = 0.16), there would be 3,262 times the plutonium in the rock phase as in the liquid phase, resulting in a 59 Ci release to the surface.

If a potash corehole was not properly plugged and were to become a conduit for surface water inflow, it could become a significant source of recharge to the Culebra. If located upgradient from the repository, this recharge could increase the gradient which would shorten water flow time to the accessible environment. Also, the larger water flow rates could increase the quantity of radionuclides being transported if Culebra solubility is limiting or it could decrease the amount being adsorbed in the solid matrix if the larger flow decreases the radionuclide concentration. If the borehole is located down gradient from the repository, recharge might be beneficial because it would decrease the gradient between the repository and the recharge point. However, this inflow of fresher water would increase the gradient between that point and the accessible environment and could also desorb previously adsorbed radionuclides.

9.3.3 <u>Water Well Drilling</u>

Only limited water well drilling occurs around the WIPP site, since most of the water in the area is too high in solids content to be suitable for drinking. Water wells may be used to support oil and gas drilling, mining operations, or stock watering. An application to drill a water well within the boundaries of a declared underground water basin, such as the Carlsbad Underground Water Basin, must be made to the State Engineer. The State Engineer requires a prospective water well driller to publish his application weekly for three weeks in a local newspaper before a permit will be granted.

Based on information obtained from the New Mexico State Engineer's Roswell District Office and various groundwater reports (HEN51, NIC61), the following observations can be made about water well drilling activities around the WIPP:

(1) Water wells are drilled for a variety of purposes. About 20% of the deeper wells (i.e., wells in the Santa Rosa sandstone and lower-lying formations) drilled since 1952 were for oil and gas applications such as drilling muds or mining purposes. About 20% were drilled for stock watering. Several percent were listed as domestic and observation use. Over 40% of these new wells are presently listed as unused and there is no indication of why they were drilled.

(2) There are essentially no data on well pumping rates. Two Rustler Formation wells in Nash Draw (in T22S, R30E) had reported pumping rates of 260 and 700 gpm. A Rustler Formation well in T23S, R30E measured 3 gpm. Two wells in the Triassic strata (in T23S, R31E and T23S, R32E) had yields of 10 gpm.

(3) No assessment has been made of water quality in these wells.

(4) There are very few data available on how extensively these wells are used. In the wells listed as not being used it is not known whether these were dry holes, whether they were ever used, or if they are likely to be used in the future.

(5) Within a given township, new wells are periodically being drilled at the same time existing wells are classified as unused.

No water well drilling in the Carlsbad Underground Water Basin reached repository depths. Therefore, water well drilling would be considered shallow drilling. A pumping water well could, depending on its location, either increase or decrease the gradient in the Culebra between the repository and the accessible environment. A borehole drilled into a contaminated plume of Culebra water would bring some contaminated fluid and solid material containing adsorbed radionuclides to the surface during drilling. For an average borehole diameter of 12.5 inches (32 cm), based on 14 wells near the WIPP site, the area of the hole is 0.079 m^2. For a 7.0 m thick Culebra aquifer with 0.16 porosity this would bring 0.089m^3 fluid in the 0.553 m^3 of solids (bulk volume) brought to the surface. For assumed solubilities of 10^{-6} M for plutonium and americium and 10^{-4} M for uranium, only 0.080 Ci would be transferred to the surface in the fluid. Radionuclide quantities adsorbed on the solids brought to the surface would be somewhat greater if some adsorption of radionuclides on the dolomitic Culebra rocks occurs.

The largest potential consequence would come from an on-site well pumping from a contaminated aquifer. The testing of a well could have significant consequences. For example, some wells on the WIPP site have been pumped at 3 gallons per minute (0.19 l/s) or greater for extended periods. Pumping of a well at this rate for 72 hours would bring 49 m^3 of water to the surface. This volume would carry about 43 Ci to the surface (accessible environment) at 1,000 years (for 10^{-6} M plutonium and americium and 10^{-4} M uranium solubilities). Greater quantities of radionuclides could be brought to the surface if a well were placed in regular production. However, the number of curies brought to the surface could be much less than suggested by this calculation if the actinide concentrations in the plume were lower (because of lower solubility limits or because most radionuclides had been removed by chemical adsorption), or if much of the water being pumped was not from the contaminated plume.

9.3.4 Other Exploratory Drilling

Limited exploratory drilling for other resources has occurred around the WIPP site and could occur in the future. For example, drilling for uranium in shallow lying sediments has been conducted in the past. No evidence of uranium was found in the gamma logs from 36 boreholes near the WIPP site which penetrated the near surface Dewey Lake Redbeds, the Santa Rosa sandstone, or the Gatuna Formation. Although uranium could occur in these types of sediments, no significant occurrence has been found in the Delaware Basin (POW78).

Sulfur is found in the Castile Formation in the Central Delaware Basin mainly in Culberson County, Texas about 50 miles south of the WIPP site (SIE78, POW78). The sulfur appears to be associated with portions of the Castile which lack halite either due to removal by dissolution or to absence during deposition. These controls predominate in the southern and western portion of the Delaware Basin. Since the WIPP site lies east of the edge of the Castile halite, occurrence of economic sulfur deposits is unlikely there.

Quantities of lithium are found dissolved in the brine reservoirs in the Castile Formation which underlies the Salado Formation containing the WIPP repository. Average lithium concentrations of 240, 280 and 360 mg/l, respectively, were reported for the ERDA-6, WIPP-12, and Union wells (DOE83). The reservoir intersected by the WIPP-12 well lies within the LWA boundary and has a "representative" estimated volume of 2.7 x 10^6 m^3 or about 17 x 10^6 bbl (DOE83). Based on the estimated reservoir volume and measured brine chemistry, the reservoir would contain about 0.75×10^6 kg of Li. This is equivalent to only about two or three months of domestic production at current rates (BOM94c). In an area of about 775 km^2 around the WIPP site, 12 of 92 boreholes penetrating the Castile Formation intercepted brine (SAN92, Vol. 3), but only a few of these holes were assayed for lithium.

A variety of other minerals are present around the WIPP site, including salt, caliche, and gypsum. However, these minerals are generally sub-economic, and no significant drilling is currently involved in their discovery and exploitation (SIE78). Depending on the depth of the drilling target, exploration for these other minerals could be classified as either shallow drilling or deep drilling as defined in 40 CFR part 194.

9.4 INTRUSION BY MINING

9.4.1 Introduction

EPA requires that consideration of mining-related scenarios should be included in assessing the performance of the WIPP repository (§194.32). This requirement applies to mining of all minerals, although the major commodity currently extracted in the Delaware Basin by underground mining is potash. Economic deposits of this mineral are confined to the northern portion of the Basin in Eddy and Lea Counties, New Mexico near the WIPP site. No other significant underground mining occurs in the Delaware Basin, although some sulfur is extracted via Frasch process wells (in the Castile Formation) in Culberson County, Texas.

As previously noted, potash is a general term for a variety of potassium bearing minerals for which the chemical compound K_2O is often used as a surrogate to characterize the potassium content. About 95% of U.S. potash sales are to the fertilizer industry with the balance primarily to the chemical industry. Historical sources of potash include kelp, wood ashes, lake brines, alunite, cement dust, sugar beet waste, blast furnace dust, and various potassium-rich minerals. Today, U.S. potash production is principally from the rock sylvinite - a mixture of the minerals sylvite (KCl) and halite (NaCl) - and from langbeinite - a potassium magnesium sulfate ($K_2SO_4 \cdot 2MgSO_4$). Potash is typically recovered either by underground excavation mining or by solution mining where water is injected into a mineralized zone and saturated brine is extracted and recrystallized in evaporation ponds. In the Delaware Basin, potash is recovered only by excavation mining.

Extensive underground potash mining is currently being conducted in the vicinity of the WIPP site. During 1992, southeastern New Mexico supplied 81% of U.S. production (DUP94). Mining operations occur in the McNutt potash zone of the Salado Formation. A generalized stratigraphic column showing these Upper Permian potash-bearing rocks and younger strata is included as Figure 9-3 (CHE78). Eleven ore zones have been identified within the McNutt. Primary current mining targets are the 10th ore zone for sylvite and the 4th ore zone for langbeinite. Some mineralization has been identified in ore zones 2, 3, 5, 8, 9, and 11 in the WIPP vicinity[2](NMB95). These mineralized zones extend within the WIPP Land Withdrawal Boundary as shown in Figure 9-4 which plots the boundaries of the current Bureau of Land Management (BLM) Lease Grade criteria[3] as estimated by Griswold (GRI95). Reserve and resource estimates inside the WIPP boundary are summarized in Table 9-1 (NMB95). When the WIPP site was selected in 1976, most of the site lay outside the boundary of the Known Potash Leasing Area (KPLA) (i.e., the area which contains lease grade reserves). However, subsequent site evaluation by DOE (then ERDA) included drilling and coring 21 exploratory holes for potash (POW78). This drilling program indicated that potash mineralization was more extensive than expected. As a consequence, the U.S. Geological Survey used these drill hole data to extend the KPLA. The KPLA now embraces all of the WIPP site although most of the southwestern quadrant of the site is barren of mineralization, as is the repository location.

The WIPP site also lies within what is called the Designated Potash Area. This area, which is defined by Order of Secretary of Interior (51 FR 39425) under the authority of two mineral leasing acts, is slightly larger than the KPLA. It should be noted that the northern most townships within the Designated Potash Area lie outside the northern boundary of the Delaware Basin[4]. According to the Secretarial Order, potash enclaves are delineated within the Designated Potash Area as regions containing currently economically minable ore

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[2] The New Mexico Bureau of Mines and Mineral Resources reserve and resource estimates are based on 40 drill holes in and around the WIPP site. Other drill holes exist in the area, but the data are proprietary. These 40 drill holes cover the WIPP Land Withdrawal area and an area extending about 1 mile outside the boundary except for the southwest quadrant of this perimeter area (GRI95).

[3] The current BLM leasing criteria for potash reserves specify ore seams containing at least 4 feet of 4% K_2O (a grade-thickness product of 16) for langbeinite and 4 feet of 10% K_2O for sylvite (a grade-thickness product of 40). These criteria have been in effect since 1969. According to BLM, sylvite is being mined below the 10% K_2O minimum cutoff grade and langbeinite is being mined below the 4% minimum (CON95).

[4] About 50% of the KPLA lies outside the Delaware Basin.

Figure 9-3. Generalized Stratigraphic Column of Permian and Younger Strata, Eddy County, New Mexico (CHE78)

Figure 9-4. Location of BLM Lease Grade Mineralization Within the WIPP Site

Table 9-1. Potash Reserves and Resources Within WIPP Site Boundary (GRI95)

AREA	TYPE OF RESOURCE	MILLION SHORT TONS	K_2O (%)
4th Ore Zone (Langbeinite)	In-place resource (>4% K_2O and actual thickness)	47.0	7.12
	BLM Lease Grade reserve (>4% K_2O and 4-foot mining height)	40.5	6.99
	Minable reserve (>6.25% K_2O and 6-foot mining height)	18.0	7.59
10th Ore Zone (Sylvite)	In-place resource (>10% K_2O and actual thickness)	53.7	14.26
	BLM Lease Grade reserve (>10% K_2O and 4-foot mining height)	52.3	13.99
	Minable reserve (>12.25% K_2O and 4.5 foot mining height)	30.6	15.00
Other Ore Zones	In-place resources[a]	18.4	5.74-15.71

a - Generally do not meet lease grade standards. According to GRI95, these resources could only be minable if advanced thin-seam mining techniques are developed in the future.

reserves. Inside these enclaves, it is Department of Interior policy to deny approval of most oil and gas drilling permit applications from surface locations with two exceptions (51 FR 39425):

"a. Drilling of vertical or directional holes shall be allowed from barren areas within the potash enclaves when the authorized officer determines that such operations will not adversely affect active mining operations in the vicinity of the proposed drillsite.

b. Drilling of vertical or directional holes shall be permitted from a drilling island located within a potash enclave when: (1) There are no barren areas within the enclave or drilling is not permitted within on the established barren area(s) within the enclave because of interference with mining operations; (2) the objective oil and gas formation cannot be reached by a well which is vertically or directionally drilled from a permitted location within the barren area(s); or (3) in the opinion of the authorized officer, the target formation beneath a remote interior lease cannot be reached by a well directionally drilled from a surface location outside the potash enclave."

For perspective, the Designated Potash Area, as of October 1986, occupied 497,002 acres as compared to the area of the WIPP site which is 10,240 acres.

Drilling on state and private lands is controlled by the New Mexico Oil Conservation Division (OCD). Because of problems in implementing then existing OCD regulations, a revised order (No. R-111-P) was approved by the State Oil Conservation Commission on April 21, 1988 (OCC88). Under the terms of R-111-P, the New Mexico "Potash Area" is coterminous with the KPLA. Within the Potash Area, drilling for oil and gas cannot be conducted at any location containing life-of-mine potash reserves (LMR) except by mutual agreement of the lessor and lessee of both the potash and oil and gas interests. Outside the LMR, drilling of shallow wells can be no closer than 0.25 miles of the LMR boundary or 110% of the ore depth, whichever is greater. (Shallow wells are defined as those in all formations above the base of the Delaware Mountain Group or less than 5,000 feet deep, whichever is less.) Deep wells must be at least 0.5 miles from the LMR boundary. One of the objectives of R-111-P was to eliminate the need for drilling islands and three-year mining plans required by the Secretarial Order on Federal lands.

Potash ore reserves in the Carlsbad KPLA were estimated to be about 100 million short tons (90.7 million metric tons) of recoverable K_2O based on 1973 prices (WEI79)[5]. At current production rates of about 1.4 million metric tons per year (DUP92), this reserve would be exhausted in about 65 years (about 15 years after projected completion of the WIPP disposal phase, but during the period of active institutional controls)[6]. In the 1993 WIPP Resource Disincentive Report, DOE commented on the finite nature of the langbeinite supply noting that langbeinite operations would continue for another 28 years if only current reserves are considered and the production period would be extended to 46 years if resources were also included (DOE93). In 1993, the New Mexico Bureau of Mines and Mineral Resources provided a breakdown of the expected operational life of each mine in the area. As shown in Table 9-2, life of the Mississippi Chemical operations is projected to be 125 years while the other five mines should wind down in 33 years or less (BAR93). It should be noted that the mine life estimates are based on published information. Data on actual mining reserves are regarded as proprietary information by the potash mining companies and actual mine life may be longer than projected here.

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[5] In a 1978 study, AIM Inc. estimated potash reserves for the Carlsbad District including those within the WIPP site to contain 109 million tons of recoverable products - a total very similar to the 1973 Bureau of Mines estimate (SEE78).

[6] In 1973, the U.S. Geological Survey stated that, based on then current production levels, crystalline deposits and brines in the U.S. would last for at least 100 years (SMI73). Nearby Canadian resources are adequate for thousands of years.

Table 9-2. Active Potash Mines in New Mexico Showing Estimated Capacity, Average Ore Grade, and Mine Life at the Average 1992 Price of $81.14/st product

Operator	County	Product Capacity (st/yr[1])	Ore Grade (% K_2O)	Mine Life (yrs)
Eddy Potash Inc.[2]	Eddy	550,000	18	4
Horizon Potash Co.	Eddy	450,000	12	6
IMC Fertilizer, Inc.	Eddy	1,000,000[3]	11[3]	33
Mississippi Chemical	Eddy	300,000	15	125
New Mexico Potash[2]	Eddy	450,000	14	25
Western Ag-Minerals[4]	Eddy	400,000	8[5]	30

Data from J.P. Searls, U.S. Bureau of Mines, oral communication, 1993.
[1] May not be operating at full capacity.
[2] Owned by Trans-Resource, Inc.
[3] Muriate, langbeinite, and sulfate combined.
[4] Owned by Rayrock Resources of Canada.
[5] Langbeinite only.

Current mining operations can be economically extended to the WIPP site boundary and it is likely that this will occur (GRI95). Although economic mineralization also lies within the WIPP site, the WIPP Land Withdrawal Act (LWA) (Public 102-579) precludes mining within the withdrawn area. However, at some future time, when active institutional controls no longer exist and if passive institutional controls are ineffective, mining of the potash inside the boundary is a conceptual possibility. The economics would, of course, be different and exploitation would probably require creation of a new infrastructure to transport ore to the surface and beneficiate it since existing facilities would have been abandoned. GRI95 estimates of <u>minable</u> reserves within the site boundary assume that new mine and plant facilities would not be needed if the reserves were exploited now. As noted in Table 9-1, minable reserve estimates are based on higher grades and greater ore seam thicknesses than for Lease Grade reserves.

Potash was first produced from the Delaware Basin in 1931 (BAR93). Measured potash reserves cover an area of approximately 200 mi^2 in the Delaware Basin with the remainder of the reserves located over the Capitan Reef or outside of the Delaware Basin. Since 1931, mining of the different potash ore zones has covered an area (in the Delaware Basin south of T20S) of over 40 mi^2 as estimated from a 1993 map of the potash resources (BLM93). Using 9700 mi^2 as the approximate area of the Delaware Basin, it can be estimated that about 0.4% of the Delaware Basin has been mined over the past 62 years (1993-1931). This produces a conservative estimate of the rate of mining of 1% of the Delaware Basin area over the past

100 years. Any mining of potash or other minerals of current interest elsewhere in the Delaware Basin would raise this percentage.

The following sections discuss potential impacts of mining on the anticipated long-term performance of the WIPP repository and elaborate on the position taken by EPA in the 40 CFR part 194 rule (§194.32(a)) that performance assessment shall consider the effects of mining on the disposal system and these effects can be limited to changes in the hydraulic conductivity of the disposal system induced by mining.

9.4.2 Mining Scenarios

Consideration of mining effects on PA involves scenarios where mining occurs up to the land withdrawal boundary and where mining occurs within the withdrawn area up to the limits of economic mineralization. Mining outside the site boundary could occur at anytime until available resources are exploited. Mining activities inside the boundary should not occur until sometime after active institutional controls are no longer practicable. The types of scenarios will generally be the same regardless of the assumed location of the mining operations and will, in the main, involve events which alter the rate and volume of radionuclide movement through groundwater to the boundary of the accessible environment. It does not appear that mining can seriously impact repository performance unless boreholes, which intrude the waste panels, are also present. Without the presence of an intruding borehole, there is no obvious way to connect the waste with the overlying water-bearing formations which can then provide a lateral transport path.

The most common mining scenario assumes that subsidence of overburden into the excavated region can alter the hydraulic conductivity of the overlying water-bearing strata (e.g., the Culebra Dolomite Member of the Rustler Formation), possibly increasing transport velocities and/or radionuclide mass-fluxes to the accessible environment. SNL summarized the situation as follows (AXN94):

> "Although the land surface in subsiding areas is lowered and there may be local changes in drainage patterns, the overall topographic features that have the primary effect on the water table will remain similar to those of the present. However, subsidence may have impacts other than lowering of the land surface, including possible fracturing of units that overlie the potash zone. This fracturing could lead to an increase in conductivity for those units. The degree of increase and the relative change in conductivity from unit to unit could have

> an effect on the long-term groundwater flow behavior for Rustler units.
>
> Because the Tamarisk and Forty-niner members presently have very low conductivities, fracturing may cause larger [percentage] increases in conductivity in those units than in the Culebra and Magenta. The effect on flow would be similar to that described for boreholes that do not intrude the repository [ref. omitted] for the same fundamental reasons. That effect would be a change in the direction of the hydraulic gradients in the land withdrawal area. Currently they direct flow in the Culebra from north to south. If the scenario were to occur, they would direct flow in the Culebra towards the southwest."

Detrimental mining-related scenarios might include:

- Increased hydraulic conductivity of water-bearing formations above the mining horizons due to subsidence (Section 9.4.4)
- Change in flow directions within water-bearing members if a vertical hydraulic connection is created by subsidence (Section 9.4.5.2)
- Formation of subsidence-related surface depressions where water could accumulate and alter local recharge characteristics (Section 9.4.5.3)
- Increased hydraulic gradient if significant flow from water-bearing strata into the mine workings occurs (Section 9.4.5.4)
- Damage to borehole or shaft seals by subsidence effects (Section 9.4.5.1)
- Problems created by solution mining (Section 9.4.5.1)
- Increased hydraulic conductivity of the Salado due to excavation induced stresses (Section 9.4.5.6)

Depending on the location of the mining operations, some of these same scenarios may actually be beneficial. Depending on the location, for example, flow of water into underground mine workings might also reduce the hydraulic gradient in the currently envisioned flow path. Of the potentially detrimental scenarios, the only one expected to be of concern is hydraulic conductivity increases in certain strata above the mining location.

The detrimental aspects of these scenarios will be discussed in more detail subsequently, but a review of relevant technical literature will be presented first to establish a framework for that discussion.

9.4.3 Literature Review

9.4.3.1 WIPP Related Studies

Final Environmental Impact Statement

In the WIPP Final Environmental Impact Statement (FEIS) published in 1980, DOE summarized, without comment, prior studies on potash mine subsidence in the area as reported by the BLM in 1975 (DOE80). At that time, it was estimated that subsidence was likely to have occurred over an area of 14 square miles and was expected over an additional 40 square-mile area. The nearest subsidence to the WIPP site occurred at a distance of 3.5 miles. Observed maximum surface subsidence varied from 2.7 to 5.3 feet. This is about two-thirds the height of the mined ore zone.

D'Appolonia Studies

The impact on the WIPP of neighboring potash mines was examined in greater detail by D'Appolonia in 1982 (DAP82). They observed that, even when subsidence occurs, the integrity of the overlying salt section is not jeopardized as demonstrated by the absence of water flow into the potash mines from units higher in the stratigraphic section.

However, D'Appolonia noted that "the opening of entries for underground potash mining causes a redistribution of stresses within the surrounding rock that can lead to opening of fissures and/or increase the hydraulic conductivity of the surrounding rock. Mining can also lead to the more gross effects of surface subsidence and subsidence-induced fracturing above the mined level." Both empirical and simple analytical techniques were used to characterize the extent of such disturbances.

Using a secondary creep law for the salt, they calculated the zone of influence in a horizontal plane around a hypothetical potash mine (at depth of 2000 ft) and a repository room to be 1,900 and 200 feet, respectively. Thus, if the horizontal separation is 2,100 feet, there would be no stress-induced interaction between the two mined regions. D'Appolonia believes this calculation to be conservative because the WIPP also has a vertical separation from the McNutt of about 400 feet.

Estimates were also made of the impact on the hydraulic conductivity of the salt from reducing the confining stress in the salt. This occurs due to stress relief around an excavation. Based on an empirical relationship between salt permeability, octahedral shear stress, and mean confining stress, D'Appolonia calculated the increase in hydraulic conductivity to be less than one order of magnitude. At a distance into the salt of six times the width of mine opening the calculated hydraulic conductivity was only about twice the conductivity of the undisturbed salt.

D'Appolonia suggested that a generalized subsidence equation developed for coal mines in the Appalachian region could be used for making preliminary estimates of the magnitude of surface subsidence as follows:

$$S = sHbe \quad (1)$$

where

- S = maximum subsidence (ft)
- s = subsidence factor (dimensionless)
- H = cavity height (ft)
- e = extraction ratio (dimensionless)
- b = fraction of cavity remaining after backfill (dimensionless)

The subsidence factor is the ratio of the actual vertical displacement to cavity height which in the Carlsbad area is about 0.67. From the equation, assuming no backfill (b=1), a mining height of 6 feet, and an extraction ratio of 90%[7] the maximum subsidence would be about 3.6 feet (1.1 m).

As noted previously, potash is sometimes recovered by solution mining although this technique is not being used in the vicinity of the WIPP. According to D'Appolonia, solution mining of langbeinite is not technically feasible because the ore is less soluble than the surrounding evaporite minerals. Solution mining of sylvite was unsuccessfully attempted in the past. Failure of solution mining was attributed to low ore grade, thinness of the ore beds, and problems with heating and pumping injection water. Unavailability of water in the area would also impede implementation of this technique. For these reasons, solution mining is not currently used in the KPLA.

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[7] According to BAR93, 60 to 75% of the ore is extracted during initial mining, but subsequent removal of the remaining pillars results in extraction ratios exceeding 90%.

IT Corporation Backfill Engineering Analysis

In 1994, IT Corporation reported the results of analytical and empirical subsidence studies of the WIPP repository (ITC94). The thrust of these studies was to evaluate the effects of various backfill options on repository subsidence. The effects of potash mines in the vicinity on repository integrity were not addressed, per se. Never-the-less, some generally applicable subsidence information was developed. IT used four techniques to analyze subsidence caused by excavation of the repository:

- Mass conservation method
- Influence function method
- National Coal Board method
- Two-dimensional numerical modeling (with the Fast Lagrangian Analysis of Continua [FLAC] computer code)

As shown in Table 9-3, reasonable agreement was obtained among the four techniques with maximum subsidence at the surface calculated to vary from 0.55 to 0.95 meters for the empty waste area.

Using the FLAC two dimensional, finite element code, the maximum vertical tensile strain in the Culebra Dolomite due to projected WIPP subsidence was calculated to be 0.0034%.

Using the influence function method,[8] ITC developed contour plots showing the areal extent of surface subsidence caused by repository excavation. The limit of subsidence area was about 850 feet beyond the southern edge of the repository footprint. From this analysis, ITC concluded that, since the maximum subsidence was about 0.4 m and since local surface topography varied by more than 3 meters, a subsidence basin would not be created and repository subsidence should not be visible.

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[8] The influence function method assumes that each point in an excavation has an identical circular area of influence on surface subsidence. These influence areas are superimposed to obtain the cumulative effect of all extraction elements.

Table 9-3. Summary of IT Corp. Subsidence Prediction Results for WIPP Repository (ITC94)

Underground Area	Contents of Excavation	Subsidence				
		Mass Conservation (m)	Influence Function Method (m)	NCB Method (m)	FLAC Single-Room Model (m)	FLAC Full-Panel Model (m)
Waste Emplacement Area[a]	Empty	0.86	0.56	0.73	0.95	0.55
	Waste Only	0.62	0.40	0.53	NA	NA
	Waste plus loose backfill	0.55	0.36	0.47	0.33	NA
	Waste plus compacted backfill	0.52	0.34	0.44	0.30	NA
Shaft Pillar Area	Empty	0.28	0.10	0.04	NA	0.13[b]
	Loose backfill	0.12	0.04	0.02	NA	NA
	Compacted backfill	0.06	0.02	0.01	NA	NA
Northern Experimental Area	Empty	0.24	0.08	0.02	NA	NA
	Loose backfill	0.11	0.04	0.01	NA	NA
	Compacted backfill	0.05	0.02	0.01	NA	NA

[a] Waste emplacement area includes Panels 1 through 8; 2 through 8 are not yet excavated.
[b] At the Waste Shaft
NCB National Coal Board
FLAC Fast Lagrangian Analysis of Continua .
NA Not Available.
m Meters.

Sandia Studies of Subsidence

Sandia has explored the possible impact of WIPP subsidence on performance assessment (PA). In a 1989 study to select events and processes which should be considered in forming possible scenarios, SNL considered three possible processes related to repository-induced subsidence (HUN89):

- Increased hydraulic conductivity of the Salado Formation
- Fracturing
- Disruption of surface drainage

Based on the fact that repository excavation would produce a maximum of a 0.2% increase in the volume of the overlying Salado salt, they concluded that increased Salado hydraulic conductivity would be insignificant. They further concluded that fracturing of the Salado could also be neglected. This conclusion was based on the expectation that the repository would adjust to excavation by creep rather than fracturing. This position was supported by observations in local potash mines where mining was conducted with two levels of extraction. The observed response of the rock in the upper horizons was flexure rather than fracture. However, SNL stated that effects on the Culebra were unknown. With regard to surface drainage, SNL concluded that this would not be a factor because, with a maximum expected surface subsidence of 2 feet, there was no integrated drainage which would be disrupted.

As noted in Section 9.4.2 above, SNL revisited the subsidence issue in 1994 concluding that subsidence could cause fracturing in the more brittle overlying units which could result in increased hydraulic conductivity and possible redirection of flow in the Culebra from a generally north to south direction to a more southwesterly direction (AXN94). Surface subsidence effects were not expected to be of sufficient magnitude to significantly alter the position of the water table.

9.4.3.2 Other Relevant Studies

IT Corporation summarized subsidence observations made at potash mines in southeastern New Mexico (ITC94). Observed angles of draw, measured from vertical edge of the mine workings to the point where surface subsidence ceased, varied from 25 to 58 degrees. ITC noted that the maximum observed subsidence over four potash mines in the area varied from

0.4 to 1.5 m which was between 16 to 66% of an assumed excavation height of 2.6 m (8.5 ft)[9]. ITC felt that the maximum observed subsidence was less than that which will ultimately occur over the excavated area.

A large body of subsidence literature has been developed based on coal mining in the United States and the United Kingdom. In a number of studies, subsidence-induced increases in transmissivity are described. Some examples are provided here.

The U.S. Geological Survey described the effects of subsidence associated with longwall mining of coal in Marshall County, West Virginia (USG88). Three tests were recounted where the transmissivity of a perched aquifer was measured before and after mining a coal seam. In each case, the overburden was about 800 feet thick and the tested aquifer was between 25 and 150 feet below the surface. In two tests, the transmissivity was found to increase significantly, from 3.7 to 160 ft^2/day in one case and from less than 0.001 to 36 ft^2/day in the other. In the third test, only a slight increase between pre- and post-mining transmissivity was observed (from 0.20 to 0.31 ft^2/day). This small change was attributed to the fact that significant subsidence fracturing had not occurred.

Booth discussed to similar studies related to longwall coal mining in the Illinois Basin (BOO92). One series of tests was conducted at a site in Jefferson County, Illinois where coal seams 9 to 10 feet thick were mined at a depth of about 725 feet. The overburden consisted primarily of low permeability shales, siltstones and limestones. An aquifer in sandstone exists about 75 feet below the surface which is confined by an overlying shale unit. Subsidence produced visible surface tension cracks. Subsurface strain measurements and borehole examination indicated fractures and bedding plane separation. In three presubsidence tests, the measured values of hydraulic conductivity in the Mt. Carmel sandstone were 2×10^{-6}, 2×10^{-5}, and 3×10^{-6} cm/s. After subsidence, measured values were 5×10^{-5}, 3×10^{-5}, and 4×10^{-5} cm/s. In another paper discussing the same site, it was reported that post-subsidence values of the hydraulic conductivity in the shale were increased by two to three orders of magnitude (KEL91).

At a second site in Saline County, IL, investigations involved subsidence related to mining a five- to six-foot coal seam at a depth of about 400 feet (BOO92). The Trivoli sandstone

[9] The maximum observation period varied from one week to more than one year.

aquifer lies above the seam and about 180 feet below the surface. Initial conductivities in the Trivoli were less than 10^{-8} cm/s and these increased to about 5×10^{-6} cm/s after mining. Booth attributed this increased conductivity to the supposition "that subsidence had probably improved the interconnectedness of permeable fractures."

The U.S. Bureau of Mines described hydrologic changes associated with longwall mining of coal in Cambria County, Pennsylvania (MAT92). The coal seams studied were at a depth of 740 to 845 feet and were overlain by fine-grained sedimentary rocks and thin coal beds. Only small changes in hydraulic conductivity of the overburden due to mining were measured. Increases were a factor of 2 to 4 and in some cases an unexplainable decrease was noted. The increased conductivity was attributed to excavation-induced creation of new passages for groundwater flow.

Elsworth and Liu used non-linear finite element modeling to estimate changes in hydraulic conductivity associated with longwall mining (ELS95). In their modeling, a 140-foot thick zone of increased horizontal conductivity caused by vertical strains was defined immediately above a 5-foot thick coal seam. The estimated conductivity increase was about an order of magnitude.

Bai and Elsworth described modeling studies involving the interrelationship between subsidence and stress dependent hydraulic conductivity (BAI94). In concept, the rock mechanics approach was similar to that taken here and described in Section 9.4.4.2 below. In the Bai and Elsworth studies, finite element analyses over representative stratigraphy were used to calculate changes in hydraulic conductivity for various fracture spacings.

9.4.4 Impact of Mining on Hydraulic Conductivity

9.4.4.1 Background Information

Based on the available site information, it appears that one of the potential detrimental results of mining near the repository could be increased hydraulic conductivity[10] in the brittle

[10] The terms hydraulic conductivity and transmissivity are sometimes used interchangeably in the text as indicators of altered flow path resistance. Transmissivity is the product of the hydraulic conductivity and aquifer thickness. In the examples presented here, the Culebra thickness is assumed to be constant so the transmissivity is a constant factor of 7.7 higher than the hydraulic conductivity (in metric units).

water-bearing strata above the mining horizons. In the analysis discussed here, the focus is on the Culebra Member of the Rustler Formation which is the most transmissive unit. The Culebra can potentially provide a lateral conduit to the accessible environment if contamination from the repository 1440 feet below reaches the transmissive horizon. According to SNL, the Culebra is a "finely crystalline, locally argillaceous (containing clay) and arenaceous (containing sand), vuggy dolomite ranging in thickness near the WIPP from about 7 m (23 ft) .... to 14 m (46 ft) ....." (SAN92). In its 1992 performance assessment (PA), SNL chose 7.7 meters as the reference thickness. Using information from 41 boreholes, SNL has calculated that the transmissivity of the Culebra varies by about six orders of magnitude depending on the degree of fracturing which exists. In the 1992 PA (SAN92), the median fracture spacing was assumed to be 0.4 m and range between 0.062 and 8 m. Thus, the median number of horizontal fractures through the Culebra thickness would be 19 and the range would lie between 1 and 124.

If subsidence occurs, it may create a network of both vertical and horizontal strains in the Culebra. Vertical tensile strains can increase the aperture of existing horizontal fractures; whereas, horizontal tensile strains can increase the aperture of existing vertical fractures. Compressive strains would have the opposite effect. Increase in fracture aperture increases hydraulic conductivity. This increased hydraulic conductivity can reduce lateral travel time of radionuclides to the accessible environment at the vertical subsurface extension of the site boundary.

As noted above, the 1992 PA assumed that flow and transport through the Culebra is through fractures. In light of this 1992 PA assumption, the following discussion focuses on one potential theory describing groundwater flow through fractures. The subsequent section discusses how the fracture aperture increases can be estimated.

Darcy's law relates the movement of water in a porous medium to the hydraulic gradient and the hydraulic conductivity. The hydraulic conductivity is a measure of the transmissive capacity of the medium coupled with the density and viscosity of the fluid (water in this case). The hydraulic gradient is simply the slope of the water table (unconfined aquifers) or the potentiometric surface for a confined system. The equation for Darcy's law is

$$q = K\frac{dh}{dl}$$

where q is the Darcy velocity (m/yr), K is the hydraulic conductivity (m/yr) and dh/dl is the hydraulic gradient (dimensionless - m/m). Hydraulic conductivity is actually a property of both the physical media (the aquifer) and the fluid. Darcy's law may also be written using intrinsic permeability (k) which is a property of the medium alone, as shown below:

$$q = \frac{k \rho g}{\mu} \frac{dh}{dl}$$

where:

k = intrinsic permeability (m^2)
ρ = fluid density (kg/m^3)
μ = viscosity (Pa·s)
g = gravitational constant (m/s^2)

The advective flow rate for a conservative contaminant (i.e., non-sorbing and nonreactive) migrating through a porous medium is computed by dividing the Darcy velocity (given above), by the effective porosity. The effective porosity for a porous medium is the ratio of the connected void space divided by the total volume of the medium.

In a fractured medium, Darcy's law still applies, however, the hydraulic conductivity of the fracture (K_f) is more difficult to determine. If the fractures are conceptualized as a series of parallel plates (with the fractures being the gaps between adjacent plates), mathematical equations can be derived to determine the equivalent hydraulic conductivity that would be used in Darcy's law.

The porosity of the fracture system actually should be viewed as two components, fracture porosity and matrix porosity. Using the parallel plate analogy, the fracture porosity is the number of fractures times the fracture aperture (gap thickness) divided by the thickness of the aquifer. The matrix porosity is the porosity of the blocks of rock between the fractures. In a fractured system such as granitic rock, the matrix porosity may be effectively zero because there is no intergranular void space. However, there is some measurable porosity space within the Culebra matrix (SAN92).

The hydraulic conductivity of a system of horizontal fractures is determined by the fracture aperture and the spacing between fractures. Given an equivalent hydraulic conductivity of the aquifer (i.e., determined through aquifer testing) and fracture spacing, it is possible to compute the fracture hydraulic conductivity. The calculation is based upon moving the same flux of groundwater through the fracture system as through a porous medium. The derivation of this equation is developed below.

The fracture conductivity equation is derived in two steps. First, the hydraulic conductivity for a single fracture is defined and then this is related to the flow rate through the fracture. The hydraulic conductivity of a single fracture is given as:

$$K_f = \frac{b^2 \rho g}{3\mu} \tag{1}$$

where:

b = half-fracture aperture (m)

K_f = fracture hydraulic conductivity (m/yr)

This equation is presented in a number of papers by Snow (SNO69) and by Gale (GAL82). The equation is often rewritten in terms of the full fracture aperture, as follows:

$$K_f = \frac{w^2 \rho g}{12\mu} \tag{2}$$

where:

w = full fracture aperture ($b^2 = w^2/4$) (m)

The second step in computing the aperture from an equivalent porous medium K value is to equate the flow rates through the porous and fractured systems. The flow through a set of N horizontal fractures of identical aperture is:

$$Q_f = \left[\frac{w^2 \rho g}{12\mu} \right] N w L \frac{dh}{dl} \tag{3}$$

where:

Q_f = flow rate through the fractures (m^3/yr)

L = length of fractures perpendicular to flow (m)

N = number of fractures

The term (NwL) is the area term in a traditional Darcy's law equation. The equation for flow through an equivalent porous medium would be:

$$Q = K_e D L \frac{dh}{dl} \tag{4}$$

where:

- K_e = equivalent porous medium hydraulic conductivity (m/yr)
- D = aquifer thickness (m)
- L = length perpendicular to flow direction (m)

As mentioned above, equation 4 may also be written in terms of intrinsic permeability (k) and fluid properties, as show below:

$$Q = \frac{k \rho g}{\mu} D L \frac{dh}{dl} \tag{4b}$$

To compute an equivalent K for the porous medium, the flow rates through the two systems (porous and fractured) must be equal. Setting equation 3 equal to equation 4 yields:

$$K_e D = \frac{w^3 \rho g N}{12 \mu} \tag{5}$$

with common terms canceling from the equations. This equation can then be rearranged to give an equation of fracture aperture in terms of an equivalent porous medium hydraulic conductivity:

$$w = \left[\frac{12 K_e \mu D}{\rho g N} \right]^{\frac{1}{3}} \tag{6}$$

Finally, to get the equation in terms of spacing between fractures (D_f = D/N), the equation becomes:

$$w = \left[\frac{12 K_e \mu D_f}{\rho g} \right]^{\frac{1}{3}} \tag{7}$$

After computing the fracture aperture for a given porous medium hydraulic conductivity (equation 7), the fracture hydraulic conductivity is computed from equation 2 above. It can be seen from equation 2 that the fracture hydraulic conductivity (K_f) varies as the square of the aperture (w) while the equivalent porous medium conductivity (K_e) varies as the cube of the aperture.

The following example provides an indication of the magnitude of changes which might be expected in the Culebra hydraulic conductivity resulting from subsidence induced fractures. For these calculations, it is assumed that the vertical tensile strain produced by subsidence results in the opening of existing horizontal fractures rather than the creation of new fractures. The total strain is accommodated by increasing the fracture aperture. Thus, if, for discussion purposes, there is a single horizontal fracture in the Culebra and subsidence from potash mining causes 0.03% vertical tensile strain (which is about 10 times the value calculated in ITC94 for the Culebra from repository subsidence, see Section 9.4.3.1 above), the total displacement is 2.3×10^{-3} m (7.7 m x 0.0003). If 10 horizontal fractures were present, then the increase in each aperture would be 2.3×10^{-4} m.

The effect of subsidence on changes in fracture aperture and hydraulic conductivity of the Culebra for the case of 10 fractures across the aquifer thickness is calculated using the following assumptions:

aquifer thickness (D)	= 7.7m
viscosity(μ)	= 0.001 Pa•s
density (ρ)	= 1000 Kg/m^3
gravitational constant (g)	= 9.79 m/s^2
equivalent hydraulic conductivity (K_e)	= 7.0 m/y = 2.24×10^{-7} m/s
tensile strain	= 0.03% = 0.0003 m/m
total displacement	= 7.7m x 0.0003 strain = 2.3×10^{-3}m

The attendant fracture aperture from equation (6) is:

$$w = \left[\frac{K_e\, 12\mu D}{\rho g N}\right]^{\frac{1}{3}} \qquad (8)$$

K_e = equivalent hydraulic conductivity
w = fracture aperture
ρ = density
g = gravitational constant
N = number of fractures
μ = viscosity
D = aquifer thickness

$$w = \left[\frac{2.24x10^{-7}\ x\ 12\ x\ 0.001\ x\ 7.7}{1000\ x\ 9.79x10} \right]^{\frac{1}{3}}$$

w = 5.96 x 10^{-5} m

For a total displacement of 2.3 x 10^{-3} m, the displacement per fracture is 2.3 x 10^{-4} m and the expanded fracture aperture resulting from the tensile strain (w_{strain}) is

$$w_{strain} = 5.96\ x\ 10^{-5} + 2.3\ x\ 10^{-4} = 2.9\ x\ 10^{-4}\ m$$

To calculate the strain-altered equivalent hydraulic conductivity, $K_{,S}$,

$$K_{,s} = \frac{w^3 \rho g N}{12 \mu D} \quad where\ w = w_{strain} = 2.9x10^{-4}$$

$$= \frac{(2.9x10^{-4})^3\ x\ 1000\ x\ 9.79\ x\ 10}{12\ x\ 0.001\ x\ 7.7} \tag{9}$$

$$K_{,s} = 2.6x10^{-5}\ m/s = 8.2x10^2\ m/y$$

Values of the equivalent hydraulic conductivity for various assumed values of N within the range used in the 1992 PA are summarized below based on 0.03% vertical tensile strain:

N (fractures)	Hydraulic Conductivity (m/y)
1	14.8 x 10^4
10	8.2 x 10^2
100	4.4 x 10^1

From this hypothetical example, it can be seem that the change in hydraulic conductivity is nearly four orders of magnitude for a single fracture and only a factor of six for 100 horizontal fractures through the thickness of the Culebra.

In order to provide a more detailed view of the impact of subsidence on repository performance, a series of modeling simulations were made. First, the strain distribution in the Culebra as a function of distance from the face of a potash mine was calculated using a two-dimensional finite element model (the UTAH2 computer code). Then, this strain distribution was assumed to be accommodated as increases in the aperture of existing fractures. Details of these analyses are presented in subsequent sections.

9.4.4.2 Strain Analysis

A preliminary analysis was conducted to estimate the effects of simulated mining of potash near the WIPP site on the hydraulic conductivity of the Culebra Member of the Rustler Formation. Simulation of longwall mining of potash was done using a two-dimensional finite element computer program, UTAH2. This program has been in use for many years and is considered quite reliable (PAR78, PAR91). In response to mining, the adjacent rock mass moves to a new equilibrium position. Maximum surface subsidence occurs above the center of a mined panel, but diminishes with distance from the panel center. However, as will be shown, maximum strains do not occur at the same location as maximum subsidence. Tensile strains may open existing joints or fractures and fracture opening is assumed to increase hydraulic conductivity. If tensile strain between existing fractures is assumed to be absorbed entirely by fractures, then the change in fracture aperture can be calculated. With the assumption of an initial aperture, the change in hydraulic conductivity can then be estimated as shown in Section 9.4.4.1.

Finite Element Analysis

The UTAH2 finite element program is a small strain, elastic-plastic computer program that uses associated flow rules in conjunction with a pressure-dependent yield criterion. Elastic and strength anisotropy may be independently specified, but one material axis is tacitly assumed to be normal to the plane of analysis. The form of the yield criterion is $J_2+I_1=1$, where J_2 is an anisotropic form of the second invariant of deviatoric stress and I_1 is an anisotropic form of the first invariant of stress. The isotropic form is a paraboloid of revolution about the hydrostatic axis in principal stress space. Essential input data include the elastic moduli as well as the strength parameters, geologic column, mining geometry, boundary conditions and the premining stress state.

<u>Material Properties</u>

For the isotropic case analyzed here, the strength parameters required are the unconfined compressive (C_o) and tensile (T_o) strengths of each material represented in the finite element mesh. The elastic parameters are Young's modulus (E) and Poisson's ratio (<) for each material. Specific weights (() of the various rock types present in the model region are also needed. The data for the four rock types assumed in the model are given in Table 9-4. Sandstone, anhydrite and halite elastic properties were obtained from a subsidence analysis of the WIPP repository conducted by the IT Corporation (ITC94). Strengths, with the exception of halite were also obtained from (ITC94). Dolomite properties and halite strength are averages of about 20 results obtained from a standard handbook (LAM78).

Table 9-4. Rock Properties By Type

Rock Type	$E(10^6$ psi)	<	$C_o(10^3$ psi)	$T_o(10^3$ psi)	((pcf)
Sandstone	3.8	0.21	15.0	5.0	144
Anhydrite	10.9	0.35	13.3	4.6	144
Dolomite	9.4	0.30	13.3	1.2	144
Halite	4.5	0.25	5.2	3.1	144

Consideration of strength and elastic modulus properties for the Culebra shows that the strain at failure under uniaxial compression is 0.14%. Under tension the strain at failure is 0.013%. Rock strength is strongly affected by confining stress, so under multiaxial compressive stress, the strain at failure should be greater than in the uniaxial case. Tensile strength is not considered sensitive to confining stress, so tensile strain at failure would also be insensitive to confining stress. These estimates of failure strain are based on the laboratory test data summarized in Table 9-4. The rock mass would have different properties depending on fractures that are present in the field, but absent in the laboratory test samples. Strains calculated using laboratory data will be lower than strains calculated using field-scale properties.

Geologic Column

The geologic column used in the analysis was adapted from the ERDA 9 borehole near the center of the WIPP site (POW78). Table 9-5 gives the depth, formation, and thickness of the different strata represented in the finite element model.

Table 9-5. Strata Depth and Thickness

Formation	Depth (ft)	Thickness (ft)
1. Dewey Lake	0	550
2. Rustler	550	58
3. Magenta	608	24
4. Rustler	632	82
5. Culebra	714	26
6. Rustler	740	120
7. Upper Salado	860	507
8. McNutt	1,367	176
9. Potash Seam	1,543	10
10. McNutt	1,553	188
11. Lower Salado	1,741	333
12. Storage Zone	2,074	104
13. Lower Salado	2,178	442
14. Storage Zone	2,620	110
15. Lower Salado	2,730	106
16. Castile	2,836	1,664[11]

As can be seen from Table 9-5, the base of the mesh includes a portion of the Castile to a depth of 4,500 ft (2836+1664). All strata below the Rustler formation were assigned halite properties from Table 9-4. The Rustler Formation was assigned anhydrite properties (except for the Culebra and Magenta which were assigned dolomite properties) and the Dewey Lake Formation was assigned sandstone properties. This assignment is the same as used in ITC94.

[11] The thickness assigned to the Castile does not include the entire unit, rather it is based on assumptions regarding the necessary modeling depth required to minimize boundary effects.

Mining Geometry

The mining panel was assumed to be 10 ft thick[12], 3,000 ft long and located near the middle of the McNutt. However, the center of the panel is assumed to be a line of symmetry, so only 1,500 ft is explicitly represented in the mesh. As a rule of thumb, the influence of an excavation extends "one diameter" from the excavation walls. At one diameter, the stress concentration about a circular hole decreases to within about 15% of the initial stress state. The "diameter" that characterizes non-circular holes is the long dimension of the hole. In this case, the "1-D" guideline suggests that panel excavation may noticeably influence the state of stress 3,000 ft away. Thus, about 3,000 ft was added to the panel depth (1,543 ft) to obtain a vertical mesh dimension of 4,500 ft. The horizontal dimension of the mesh extends 5,250 ft beyond the panel edge and is thus 6,750 ft. The mesh and panel are shown in Figures 9-5 and 9-6 where the scale is 900 ft per inch. There are 4,050 elements and 4,216 nodes in the mesh. The element aspect ratio is 5 or less.

Premining Stress State

The premining stress state was attributed to gravity alone; no tectonic stresses were assumed. The vertical stress is then simply the average unit weight of rock times depth. Under complete lateral restraint, the horizontal premining stress is a constant, K_o, times the vertical stress. The constant depends on Poisson's ratio, $<$, and is therefore different for each rock type. In fact, $K_o = </(1-<)$, which ranges from about 0.2 to 0.5 based on the values in Table 9-4.

Boundary Conditions

The centerline of a panel was a line of symmetry; no displacement was allowed normal to this line. Zero displacement boundary conditions were also specified normal to the mesh bottom and far side. A zero normal displacement is often represented by a roller. The top of the mesh coincided with the ground surface and was unrestricted except at the sides.

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[12] This thickness was selected as a conservative value based on mine workings in the area (Section 9.4.3.2) and to reflect the possibility of mining on multiple levels.

Figure 9-5. Finite Element Mesh Used for Strain Analysis Mesh 4,500 ft by 6,750 ft. Scale: 1 inch = 900 ft.

Figure 9-6. Half Width (1,500 ft) of Mined Panel. Scale: 1 inch = 900 ft.

Displacement boundary conditions were also specified on the excavation surface. The panel roof was specified to "sag" 9 inches per load step; the floor was specified to "heave" 3 inches per load step. Thus, 1 foot of closure occurred during each load step at every pair of nodes along the panel except at the panel edge where traction boundary conditions, equal but opposite in sense to the premining stresses, were applied. The amount of seam level closure is controlled by the number of load steps specified, but is physically limited to a maximum of 100% of the mined thickness (10ft).

A second physical constraint on seam closure is the amount of subsidence observed at the surface. The number of load steps was adjusted to meet these constraints. Specifically, seam level closure (relative displacement between roof and floor) is 70% when 7 load steps are applied. The corresponding surface subsidence calculated at the panel centerline is 52.5% of the seam thickness. When 9 load steps are applied, seam level closure is 90%, while surface subsidence is 67.5% of seam thickness. This range of surface subsidence is considered reasonable for full-extraction potash mining.

Fracture Conductivity Change

As described above in Section 9.4.4.1, the parallel plate model for fracture flow states that average flow velocity is proportional to the square of the width (aperture) of the fracture; the volume flow rate (discharge) is proportional to the cube of the aperture (equation 3). Fracture hydraulic conductivity, K_f, is used here to relate flow velocity to hydraulic gradient and is thus proportional to the square of fracture aperture (equation 2). The relative change in hydraulic conductivity is $(K_f - K_{fo})/K_{fo}$ where K_{fo} is the premining fracture hydraulic conductivity. A purely geometrical calculation gives the relative change. Thus, the relative change in fracture hydraulic conductivity is $(w^2-w_o^2)/w_o^2$, where w is the fracture aperture after mining (i.e. w_{strain}) and w_o is premining fracture aperture. This ratio is independent of the units used for hydraulic conductivity such as feet or meters per year.
The post-mining aperture is simply the premining aperture plus the change in aperture, $)w$, induced by mining. This change is the strain, ,, integrated over fracture spacing, D_f, that is, $)w = D_{f},$. Fracture spacing was assumed to vary between 3 and 300 inches (ca. 0.08 m and 8 m); initial aperture was assumed to vary from 10^{-4} to 10^{-2} inches[13]. Strains are obtained from

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[13] In metric units these apertures are equivalent to 2.5×10^{-6} to 2.5×10^{-4} m. This range of apertures would be associated with equivalent hydraulic conductivities varying from about 6 m/y to about 60,000 m/y. In SAN92, reported hydraulic conductivities (converted from transmissivities using an aquifer thickness of 7.7 m) within the WIPP Land Withdrawal Area ranged from 0.026 to 4,400 m/y.

the finite element simulation of longwall potash mining.

Results

Two simulations were done. The first case was associated with a subsidence factor (S) of 52.5% (maximum surface subsidence as a percentage of mined panel height); the second case was associated with a subsidence factor of 67.5%. The results are similar in trend, but differ quantitatively.

Case 1.

Horizontal and vertical strains in the Culebra formation are shown in Figure 9-7 for this case (S = 52.5%). The data are strains which are calculated at the centroid of the model elements in the Culebra. Tensile strain is positive in Figure 9-7. The horizontal axis begins at the left edge of the finite element mesh, that is, at the center of the mined panel. Mining extends 3,000 ft, 1,500 ft of which is incorporated into the mesh. Figure 9-7 shows tensile strain in the vertical direction over the mined panel (between 0 and 1500 ft) and horizontal tensile strain beyond the edge of the panel (beyond 1500 ft). The peak vertical tension is about 0.055% (550 micro-in./in) and occurs 1,075 ft from the panel center (i.e., 425 ft inside the panel edge). The peak horizontal tensile strain occurs 175 ft outside the panel edge and is 0.0085% (85 micro-in/in). The horizontal tensile strain initially decreases with distance from this peak and then rises to a broad secondary maximum of about 0.0047% (47 micro-in/in) at 4,275 ft from the panel center after which it decays slowly with increasing distance.

The horizontal strain changes from tension outside the mined panel to compression inside as seen in Figure 9-7. The peak horizontal compression occurs inside the panel and gradually decreases to a minimum at the panel center where the slope of the plot is zero. This trend is indicative of a panel that is sufficiently wide relative to depth to cause maximum subsidence. The panel has super-critical width in subsidence terminology. Critical width is usually given in terms of the angle of draw: $W_c = (2H)\tan(*)$. If the angle of draw is 35°, e.g., then critical width is 1.4H where H is the overburden thickness.

Vertical tensile strains would tend to open horizontal fractures, while horizontal tensile strains would tend to open vertical fractures. Compressive strains would tend to close fractures. The magnitude of the vertical tensile strain near the center of the mining panel is about the same as the horizontal compressive strain outside the mining panel and away from

Figure 9-7. Subsidence-induced Culebra strains for subsidence factor of 52.5%. (Panel extends +/-1,500 ft from origin) the rib. So the change in hydraulic conductivity of horizontal joints over the panel is about the same as the change in vertical joint conductivity for a substantial distance outside the mining panel (neglecting peaks near the rib).

Figure 9-8 shows the change in *vertical* fracture apertures (opening or closing) in the Culebra as a function of distance from the panel center for three assumed joint spacings (3, 30 and 300 inches). Because vertical fractures or joints respond to horizontal strain, joint closure occurs over the mined panel where the horizontal strain is compressive. Vertical joints tend to open outside the mined panel. The magnitude of aperture change increases significantly with joint spacing. Vertical joint opening which occurs outside the mined panel ranges from nil to almost 0.03 inches near the rib.

Figure 9-9 shows the aperture change for horizontal joints (which respond to vertical strain). The peak aperture changes at a 300-inch joint spacing are cut off in the plot. Horizontal joint opening which occurs above the mined panel ranges from nil to well over 0.04 inches.

Figure 9-10 is a semilog plot of the relative increase in hydraulic conductivity of vertical fractures, spaced 3 inches apart, that is induced by horizontal tensile strain outside the mined panel. The relative change depends on the initial fracture aperture; 3 apertures ranging from 10^{-4} to 10^{-2} inches are assumed in the construction of Figure 9-10. Only fractional increases occur below the x-axis in Figure 9-10 (i.e., changes are less than an order of magnitude), while orders of magnitude increase are shown above the x-axis. Figures 9-10b and 9-10c present similar results at joint spacings of 30 and 300 inches. Generally, the relative increase is greater for smaller, more widely spaced joints or fractures.

Figure 9-8. Aperture Change in Vertical Joints for Fracture Spacings of 3, 30, and 300 inches and Subsidence Factor of 52.5%

Figure 9-9. Aperture Change in Horizontal Joints for Fracture Spacings of 3, 30, and

300 inches and a Subsidence Factor of 52.5%

Figure 9-10. Relative Change in Fracture Hydraulic Conductivity for Vertical Joints with various Fracture Spacings, Subsidence Factor of 52.5%, and Fracture Apertures of 10^{-4}, 10^{-3}, and 10^{-2} in. a) 3 inch b) 30 inch c) 300 inch

Figures 9-11a, b, and c show the relative increase in hydraulic conductivity of horizontal joints over the mined panel. Joint spacings of 3, 30 and 300 inches were used for Figures 9-11a, b and c, respectively.

Case 2.

Horizontal and vertical strains in the Culebra formation are shown in Figure 9-12 for this case (S = 67.5%). The peak vertical tension is about 0.071% (710 micro-in/in) and occurs inside the panel as seen in this figure. The peak horizontal tensile strain is about 0.0053% (53 micro-in/in) and occurs 225 feet beyond the panel edge. With distance, the horizontal strain becomes compressive, then reverses to tensile, and reaches a secondary maximum of 0.0053% (53 micro-in/in) at 4,375 ft from the panel center. A gradual decrease occurs thereafter. The trends in vertical and horizontal strain are similar to Case 1. However, increasing the subsidence factor increased the peak vertical tension over the mined panel but decreased the peak horizontal tension outside the mined region. The secondary peaks outside the mined region changed very little.

Since the horizontal tensile strain did not decay with distance as much as expected (see Figure 9-12), the strain analysis was repeated with a larger mesh 9,000 ft by 13,500 ft. As shown in Figure 9-13, with the larger mesh, the horizontal tensile strain decayed to 7 micro-in/in at 7,025 feet from the panel center.

Figure 9-14 shows the change in *vertical* fracture aperture (opening or closing) in the Culebra formation as a function of distance from the panel center for three assumed joint spacings (3, 30 and 300 inches). Vertical joint opening which occurs outside the mined panel ranges from nil to about 0.015 inches which is a smaller range than in Case 1 because of the smaller peak horizontal tensile strain.

Figure 9-15 shows the results for horizontal joints which respond to vertical strain. The peak aperture changes at a 300 inch joint spacing are cut off in the plot. Horizontal joint opening which occurs above the mined panel ranges from nil to well over 0.04 inches.

Figure 9-11. Relative Change in Fracture Hydraulic Conductivity for Horizontal Joints with various Fracture Spacings, Subsidence Factor of 52.5%, and Fracture Apertures of

10^{-4}, 10^{-3}, and 10^{-2} in. a) 3 inch b) 30 inch c) 300 inch

Figure 9-12. Subsidence-induced Culebra Strains for Subsidence Factor of 67.5%
(Panel extends +/-1,500 ft from origin)

Figure 9-13. Subsidence-induced Culebra Strains for Subsidence Factor of 67.5%.

(Panel extends +/-1,500 ft from origin.) Horizontal Mesh Extended to 13,500 ft.

Figure 9-14. Aperture Change in Vertical Joints for Fracture Spacings of 3, 30, and 300 inches and Subsidence Factor of 67.5%

Figure 9-15. Aperture Change in Horizontal Joints for Fracture Spacings of 3, 30, and 300 inches and a Subsidence Factor of 67.5%

Comparison with Case 1, at a 30 inch joint spacing, shows greater horizontal joint opening in this case (somewhat more than 0.02 inches compared with somewhat less than 0.02 inches in Case 1).

Figure 9-16 shows the relative increase in hydraulic conductivity of vertical fractures, spaced 3 inches, that is induced by horizontal tensile strain outside the mined panel. The gap in the plot occurs as the horizontal strain outside the panel changes from tension to compression and then back to tension with distance from the panel edge. The magnitudes of the relative change in hydraulic conductivity of the joints are similar to the previous case. Figures 9-16b and 9-16c present similar results at joint spacings of 30 and 300 inches. As before, the relative increase is greater for smaller, more widely spaced joints or fractures. Relative fracture conductivity changes for horizontal joints are included in Figures 9-17a, b, and c.

Conclusion

Simulation of full extraction mining of 10 ft of potash at a depth of about 1,500 ft near the WIPP shows large vertical tensile strains over the mined panel and slowly decreasing horizontal tensile strains beyond the panel edge. Although generally in the elastic range, the strains, when integrated between assumed fractures, lead to displacements that are significant relative to existing fracture apertures.

9.4.5 Consideration of Other Mining Impacts

In addition to subsidence-induced increased hydraulic conductivity of the Culebra, several other potentially detrimental scenarios were postulated in Section 9.4.2 above. These are discussed in the context of the information presented here.

9.4.5.1 Solution Mining

As described earlier, solution mining of langbeinite is not technically feasible because the evaporite minerals which surround the ore are more soluble than the ore itself. Attempts to solution mine sylvite have not met with success because of the characteristics of the ore body. Thus, it appears unlikely that this technique will be applied to potash ores in the region around the WIPP.

Figure 9-16. Relative Change in Fracture Hydraulic Conductivity for Vertical Joints with various Fracture Spacings, Subsidence Factor of 67.5%, and Fracture Apertures of 10^{-4}, 10^{-3}, and 10^{-2} in. a) 3 inch b) 30 inch c) 300 inch

Figure 9-17. Relative Change in Fracture Hydraulic Conductivity for Horizontal Joints with various Fracture Spacings, Subsidence Factor of 67.5%, and Fracture Apertures of 10^{-4}, 10^{-3}, and 10^{-2} in. a) 3 inch b) 30 inch c) 300 inch

9.4.5.2 Change in Flow Direction of Water-Bearing Members if a Vertical Hydraulic Connection Is Created By Subsidence

As discussed in the Section 9.4.2, if a hydraulic connection did occur, the result could be a shifting of flow in the Culebra toward the southwest. According to information presented by Reeves et al. (REV91), the current travel path is toward the southeast and entails a distance about 3,600 m from the center of the waste area to the southern boundary of the withdrawn area. If subsidence produced a hydraulic connection between the water-bearing members of the Rustler Formation and flow shifted toward the southwest, then the travel distance could be shortened to 2,415 m which is the shortest distance from the southernmost panel in the waste area to the southern boundary of the land withdrawal area. This would represent a 33% decrease in travel distance to the accessible environment. However, this shift would also move the contaminant travel paths into zones of lower hydraulic conductivities which would result in longer travel times to the accessible environment (REV91).

9.4.5.3 Formation of Subsidence-Related Surface Depressions Where Water Could Accumulate and Alter Local recharge Characteristics

As noted in Section 9.4.3.2, the maximum observed surface subsidence over existing potash mines in the area is 1.5 m. Using what are believed to be conservative factors (from Sections 9.4.3.1 and 9.4.3.2) in equation 1, including an extraction ratio 90%, a mine height of 2.6 m (8.5 ft), and a subsidence factor of 0.67, the calculated surface subsidence would be 1.6 m. Subsidence of this order is less than the quoted surface relief in the area of 3 meters. Thus, topographical depressions where significant surface water could accumulate and alter local recharge are not likely.

9.4.5.4 Increased Hydraulic Gradient If Significant Flow From Water-Bearing Strata into Mine Workings Occurs

Flow of water from the Culebra and Magenta Members of the Rustler Formation into open shafts has been observed for all four shafts at the WIPP site (CAU90). Leakage into shafts for various area potash mines has also been reported (CAU90). Quoted leakage values for the open WIPP shafts are:

- construction and salt handling shaft - 0.019 to 0.11 l/s (599.0-3469.0 m^3/yr)
- waste handling shaft - 0.019 to 0.038 l/s (599.0-1198.0 m^3/yr)
- exhaust shaft - 0.026 to 0.030 l/s (820.0-946.0 m^3/yr)

- air-intake shaft - 0.030 to 0.056 l/s (946.0-1766.0 m^3/yr)

Flows of this magnitude would not persist if the shafts can be adequately sealed after mining operations have ceased or once the formation is dewatered. The Bureau of Land Management does not currently have in place specific regulations for sealing abandoned mine shafts in the KPLA. Rather, abandonment procedures are initiated by the mining companies and the sealing plans are developed on a case by case basis with the BLM (GRI96, CRA96). For example, a current operation involves local removal of the shaft liner and replacement with a concrete plug which extends from the top of the Salado Formation to the bottom of the Culebra Member of the Rustler Formation. The plug is 16 to 30 feet in length. The water bearing formations above the plug will be sealed by grouting to prevent the buildup of water on the top of the plug. Procedures for future sealing operations may be different. There is no available evidence as to the longevity of these types of seals. It is reasonable to assume, however, that even degraded seals would somewhat impede flow into the shafts.

Since it is not clear that currently contemplated shaft seals will prevent leakage for long periods, it is necessary to consider the impacts of leakage on hydraulic gradients and travel times to the site boundary. To investigate the potential impacts that mining operations may have on groundwater gradients and subsequent contaminant migration rates, a two-dimensional modeling analysis was performed. The analysis assumes that the system is confined and under steady-state conditions. The model also assumes that all groundwater flow is horizontal and occurs within the matrix (i.e, unfractured flow). The Culebra is represented as a homogeneous and isotropic porous medium at a constant thickness of 7.7 m, and an effective porosity of 13.9 percent. A series of simulations were performed in which the hydraulic conductivities (K) were varied from 7 to 500 m/yr to reflect their potential impact on altering contaminant migration rates (Table 9-6).

Since the rate at which radionuclides are transported by groundwater is directly proportional to the hydraulic gradient, any perturbances to the gradient will have a commensurate effect on migration rates. Furthermore, depending upon location, the presence of mining shafts in the vicinity of WIPP could have either a beneficial or detrimental effect on the performance assessment. Shafts located upgradient from a hypothetical human intrusion (i.e., borehole) would tend to lower or even possibly reverse the hydraulic gradients, thus, reducing the contaminant velocities and subsequent radionuclide releases at the WIPP land withdrawal boundary. Alternatively, shafts located downgradient from an intrusion would result in increased gradients towards the shaft which would tend to accelerate groundwater velocities.

Table 9-6. Summary of Results for Mine Shaft Leakage Scenario

Hydraulic Conductivity (m/y)	Time to Travel 2 km without Shaft (yr)	Groundwater Velocity without Shaft (m/y)	Time to Travel 2 km with Shaft (yr)	Groundwater Velocity with Shaft (m/y)	Flow rate into Shaft (m^3/y)
7	12400.0	0.16	9800.0	0.2	161.0
20	4350.0	0.459	3430.0	0.583	460.0
50	1750.0	1.14	1370.0	1.45	1150.0
500	175.0	11.4	137.0	14.45	11500.0

The shortest distance from the southernmost panel of the WIPP repository to the WIPP land withdrawal boundary is due south, approximately 2400 m. The ambient groundwater gradient also has a strong southerly component. Therefore, for this modeling exercise, the hypothetical mine shaft is located 2000 m downgradient from the waste disposal area. This distance was selected to maximize the effects that would occur if the groundwater gradients were affected by mining; in that the mine shaft is not so far away as to have little effect on flow, yet it is not so close as to create a zone of influence in which contaminants flowing past the mine shaft would actually travel slower due to the diminishing gradient effects that will occur downgradient of the mine shaft.

To maximize the effect that the mine could have on the hydraulic gradients, the drawdown at the mine was set almost at the base of the Culebra at 7.7 m, leaving a seepage face of 0.1 m at the shaft. The flow rate due to this drawdown was then computed by the model (Table 9-6). For example, where K = 7 m/yr, the calculated flow rate is 161 m^3/yr. Because the drawdown was maximized, this value represents a reasonable upperbound for the volume of water that would flow into the open shaft at a Culebra transmissivity (hydraulic conductivity multiplied by unit thickness) of 53.9 m^2/yr.

The hydraulic gradient was also computed at selected points upgradient of the hypothesized mine shaft and compared to the ambient gradient of 0.0032 under current non-mining conditions. Since the functional relationship between drawdown and transmissivity can be linearly extrapolated to any value of hydraulic conductivity, the overall effect on gradients that is imposed by varying hydraulic conductivities is virtually identical. To illustrate this relationship, the ratio of the gradient under mining conditions to the original gradient of 0.0032 was computed and is shown on Figure 9-18.

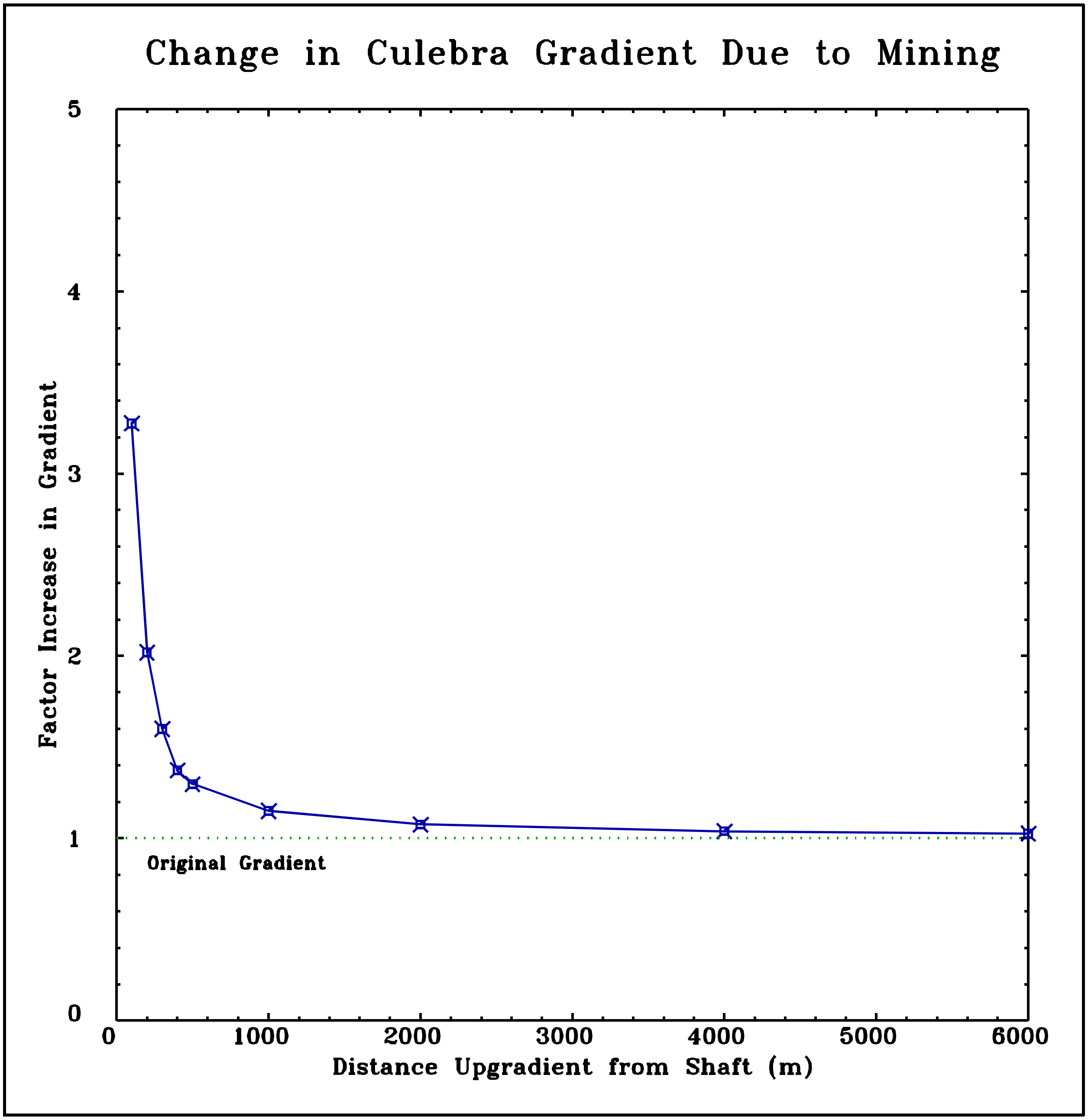

Figure 9-18. The ratio of the hydraulic gradient imposed by mining to the ambient gradient.

To investigate the effect that this change in gradient would have on migration rates, a particle-tracking analysis was performed. This type of analysis moves a particle at the same velocity as the groundwater and the rate is not affected by dispersion, diffusion, or retardation. The results from this travel time analysis are presented in Table 9-6.

In each case, the contaminant would travel approximately 27% faster over the 2000 m distance when the hydraulic gradient is affected by a mine shaft placed in a location chosen to represent mining's maximum expected effect on the hydraulic gradients. The increase for each of the simulations 27% above velocities calculated at ambient gradients and is shown in column 5 of Table 9-6. This increase is small when compared to changes in velocity due to potential increases in the hydraulic conductivity. As required by the rule, hydraulic conductivities will be increased by up to a 1000 fold above their current measured values. To place this travel time change caused by the mine shaft in perspective, groundwater velocities for each of the simulations have been recalculated using hydraulic conductivities that range from 2 to 1000 times their original values and are shown in Table 9-7. In each example, the lowest values for the recalculated velocities fall well above the velocity values that are increased by 27% due to the change in gradient. This velocity comparison indicates that increases in hydraulic conductivity over the range specified by EPA have far greater potential effects on groundwater velocities than increases in the velocities caused by altered hydraulic gradients due to mine shaft leakage. In light of the EPA requirement that DOE perform analyses that are more stringent in evaluating mining effects than those associated with an increase in gradient, it is reasonable to assume that the consequences a 27% decrease in travel time will have on the overall performance assessment will be captured by those additional analyses.

Table 9-7. Groundwater Velocities at Hydraulic Conductives the Range from 2-1000 times those values presented in Table 9-6.

Hydraulic Conductivity (m/y)	Groundwater Velocity
14.0-7000	0.32-161.0
40.0-20,000	0.92-460.0
100.0-50,000	2.30-1151.0
1000.0-500,000	23.0-11510.0

9.4.5.5 Damage to Borehole or Shaft Seals by Subsidence

From the information supporting Figure 9-4, it can be shown that the closest approach of the sylvite reserves (a grade x thickness product of 40) to waste shaft is slightly over 2,500 feet. The top of this sylvite ore zone (the 10th) lies about 1,900 feet below the surface (GRI95). Based on a 45° angle of draw, the impacted area from mining the BLM lease grade reserves would be about 600 feet from the waste shaft at the surface and at proportionately greater distances below the surface where maintenance of the shaft seal is more important (e.g., through the Rustler Formation). Alternatively, if one assumed the most pessimistic angle of draw (58°) reported for the area in ITC94, the maximum extent of the impacted area would be 3,040 feet and the disturbed zone would intersect the waste shaft at about 340 feet below the surface. The juncture is still some 200 feet above the top of the Rustler Formation and thus shaft seals should not be affected at any critical location in transmissive members of this formation.

If all the BLM lease grade reserves within the repository were mined out, a number of boreholes would be undercut by the mining operations and the sealed area of the borehole subject to subsidence-induced strains. Some of these impacted boreholes are shown in Figure 9-4. However, the borehole seals between the repository and the mine workings should not be affected by the mining operations[14].

Thus, it is not expected that mining would breach shaft seals at any critical point along the sealed length and would not affect borehole seals between the repository horizon and the mine workings (about 430 feet). Consequently, pathways would not be opened to the repository by a mining related seal failure mechanism which would facilitate release of radionuclides.

9.4.5.6 Increased Hydraulic Conductivity of the Salado Formation Due to Excavation-Induced Stresses

As discussed in Section 9.4.3.1, the maximum increase in the hydraulic conductivity of the Salado Formation due to stress redistribution around underground openings is expected to be about an order of magnitude and this altered conductivity decreases rapidly as one moves

[14] Inside the withdrawn area, only four boreholes associated with the WIPP Project (WIPP 12, 13, DOE 1, and ERDA 9) and two earlier oil and gas holes reached or exceeded the depth of the repository.

away from the mined opening. At a distance equal to six times the width of the opening, the altered conductivity is only twice that of undisturbed salt. Even with changes of this magnitude, the salt would remain highly impermeable. In addition, creep should cause the salt to revert to near the undisturbed state.

9.4.6 Summary

Extensive potash mining operations are being conducted in the vicinity of the WIPP site with current mine workings less than 1.5 miles from the site boundary (DOE95). Existing potash leases abut the site boundary around much of its perimeter (SIL94) and its is expected that current mining operations will be extended to the land withdrawal boundary.

Reserves and resources of both sylvite and langbeinite exist within the land withdrawal boundary. Based on current BLM lease grade standards (four feet of 4% K_2O for langbeinite and four feet of 10% K_2O for sylvite), the langbeinite reserves are within 3,490 feet of the waste repository footprint and sylvite reserves are within 1,330 feet of the footprint. These reserves cannot be exploited currently because the WIPP LWA prohibits mining within the withdrawn area.

At some time in the future, after active institutional controls are no longer practicable and, if passive institutional controls have failed to warn about the buried hazards, it is a conceptual possibility that mining of the ore remaining within the withdrawn area could occur. Such a hypothetical mining operation would probably require development of a new infrastructure since existing reserves outside the withdrawn area would likely have been depleted prior to the failure of institutional controls.

The most likely detrimental impact of such future mining would be increased hydraulic conductivity of the Culebra Member of the Rustler Formation resulting from subsidence-induced fracturing of the relatively brittle dolomite. This fracturing (or widening of existing fractures) could reduce the lateral transit time for radionuclides to the accessible environment. The increased hydraulic conductivity is of no consequence unless a hydraulic connection exists between the Culebra and the repository 1,440 feet below. Based on current WIPP scenarios, the hydraulic connection could be created by an inadvertently drilled borehole which intersected the repository. Thus performance assessment will need to address the probability and consequence of such a combination of events. Based on studies reviewed here, it does not appear that other mining-related scenarios will have significant detrimental

effects on the natural and man-made barriers protecting the repository.
Simulation of full extraction mining of 10 ft of potash at a depth of about 1,500 ft near the WIPP shows vertical tensile strains over the mined panel and slowly decreasing horizontal tensile strains beyond the panel edge. Although generally in the elastic range, the strains, when integrated between assumed fractures, lead to displacements that are significant relative to reasonable fracture apertures. This, in turn, can increase the fracture hydraulic conductivity of the Culebra.

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